HETA 96-0198-2651
Portsmouth Gaseous Diffusion Plant
Piketon, Ohio

John Cardarelli II, M.S.

PREFACE

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ACKNOWLEDGMENTS AND AVAILABILITY OF REPORT

This report was prepared by John Cardarelli II, of the Health-Related Energy Research Branch (HERB), Division of Surveillance, Hazard Evaluations and Field Studies (DSHEFS). Desktop publishing by Kathy Mitchell.

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Health Hazard Evaluation Report 96-0198-2651
Portsmouth Gaseous Diffusion Plant
Piketon, Ohio

John Cardarelli II, MS

SUMMARY

On June 12, 1996, the National Institute for Occupational Safety and Health (NIOSH) received a request for a Health Hazard Evaluation (HHE) to evaluate worker exposures to neutron radiation at the Portsmouth gaseous diffusion plant (PORTS) operated by the Lockheed Martin Utility Services, Inc. (LMUS) in Piketon, Ohio. Another contractor, Lockheed Martin Energy Systems (LMES), operates certain areas at this facility maintained by the Department of Energy (DOE). Workers and areas under LMES were also included in this HHE. The request was submitted by two separate union safety representatives and described the hazard as a chronic exposure to neutron radiation during various production, maintenance and security activities. It also stated that neutron doses have not been recorded in the workers' dose histories for the past 40 years. In response to this request, NIOSH conducted two site visits between November 1996 and February 1997 to:

1. Determine if potential neutron exposures exist at the site.
2. Identify neutron sources.
3. Identify work areas or job titles having the greatest potential for neutron exposures.
4. Quantify neutron doses by work area or job title.
5. Determine past reporting and recording practices regarding neutron doses.
6. Assess the feasibility of reconstructing past neutron doses.

The following paragraphs describe, summarize, and discuss the findings, results and conclusions associated with each of the listed objectives.

Determine if potential neutron exposures exist at the site: The LMUS PORTS is one of two operating uranium enrichment production facilities in the United States that use the gaseous diffusion process to enrich uranium. Uranium as found in nature, U_{nat}, is a radioactive element that contains a mixture of three isotopes: ^{238}U, ^{235}U, and ^{234}U. The process is designed to enrich the ^{235}U isotope for use in the nation's commercial and defense nuclear programs. Uranium is primarily responsible for the presence of neutrons at the PORTS. Neutrons are produced mainly from a nuclear reaction when its decay product (an alpha particle) reacts with bonded fluorine atoms. Additionally, neutrons are produced when uranium spontaneously splits into two lighter elements (a spontaneous fission). Since these processes occur naturally, neutron radiation has been and continues to be present at the site.

Identify neutron sources: It is clear from the physical nature and characteristics of uranium and its compounds that appreciable neutron radiation is most likely to be present in areas where uranium is stored (cylinder yards), routinely handled (feed and withdrawal areas) or in areas where uranium forms deposits within the cascade. The point at which this source becomes a radiological concern depends on several factors including neutron production rates, enrichment, neutron moderation factors, geometry, deposit size, detection capabilities, time of exposure, and distance from the source.

Identify work areas or job titles having the greatest potential for neutron exposures: During the November 1996 initial survey, locations for area and personnel monitoring were selected by representatives of management and the two unions. Their selections were based primarily on uranium being present in large quantities and job titles having routine tasks in those areas. Area neutron measurements were conducted in the following locations: process buildings (X-326 and X-330), uranium storage areas (X-745 and X-345), and work areas routinely occupied by workers with selected job titles (Buildings X-705, X-344, and X-343). The job titles selected for monitoring included: Uranium Material Handler, Process Operator, Health Physics Technician, Chemical Operator, and Security Guard.

Quantify neutron doses by work area or job title: In the process buildings (X-326 and X-330), measured neutron doses ranged from below the limit of detection [0.2 millisieverts (mSv)] to 0.6 mSv. The highest neutron doses (2.1 to 7.1 mSv) were found in the uranium storage area maintained by the DOE (X-745). In all other locations (X-343, X-345 and X-705), measured neutron doses were at or below the limit of detection. None of the personnel monitored during this evaluation received neutron doses above the limit of detection. Although the results of a recent study conducted by the site in 1995 showed that measurable neutron doses were received by workers performing activities similar to those monitored during this evaluation.

Determine past reporting and recording practices regarding neutron doses: Neutron exposures have always occurred at the PORTS facility but the occupational doses have been "considered insignificant in comparison with DOE radiation protection standards" to justify routine monitoring. Therefore, personnel neutron dosimetry was not conducted at this or any other gaseous diffusion plant in the past. Recording decisions regarding high doses (>2.7 rem) were based on the philosophy that doses of this size were very unlikely when compared with past doses reported and recorded at the site. Therefore, equipment failure was often provided as the reason for the abnormal dose rather than investigating the anomaly.

Assess the feasibility of reconstructing past neutron doses: In early 1981, PORTS introduced thermoluminescent dosimeters (TLDs) to replace film-based dosimeters as a part of the routine radiation monitoring program. The early film badges (1950s-1980) and the first TLD badges (1981-1990) were not calibrated for and could not measure neutron exposures. Despite that limitation, an effort to reconstruct past neutron exposures was attempted by requesting historical computerized data of TLD chip readings from 1981 to the present. Data available for this purpose was limited to only the most recent data (1992-1995). Thus, it was not feasible to reconstruct potential neutron before 1992.

This health hazard evaluation has shown that under certain conditions an acute exposure to neutron radiation can occur. Therefore, a potential health hazard to neutron radiation exists at this site.

Recommendations include: employ an appropriate phantom material to monitor neutron exposures in the X-345 vault areas properly; inform workers potentially exposed to neutrons about the proper positioning of the TLDs and its angular dependence in detecting incident neutrons; revise minor errors in the neutron dose algorithm documentation; review and improve linkage issues regarding unaccounted personal doses; reevaluate the use of archive tapes to prevent further loss of historical dosimetry data; continue neutron monitoring in areas where uranium is routinely stored or handled; reevaluate past maintenance activities and personnel involved in physically removing uranium deposits for exposures associated with the *slow cooker* phenomenon; and report administrative changes or decisions regarding issues in the health physics dosimetry program (doses below the limit of detection, abnormal chip ratios, investigative reports, etc.) to the workforce to educate, inform, and solicit questions about how the changes or decisions will affect their dose histories.

Keywords: SIC 2819 (industrial inorganic chemicals, not elsewhere classified), neutrons, TLD, thermoluminescent dosimetry, TED, track-etch dosimetry, neutron dosimetry, radiation exposures, gaseous diffusion, uranium enrichment, fission, spontaneous fission, slow cookers, criticality.

TABLE OF CONTENTS

INTRODUCTION

On June 12, 1996, the National Institute for Occupational Safety and Health (NIOSH) received a request for a Health Hazard Evaluation (HHE) to evaluate worker exposures to neutron radiation at the Portsmouth gaseous diffusion plant (PORTS) operated by the Lockheed Martin Utility Services, Inc. (LMUS) in Piketon, Ohio. Worker representation was provided by the two unions at the site, Local 3-689 of the Oil, Chemical, and Atomic Workers Union International (OCAW) and Local 66 of the United Plant Guard Workers of America (UPGWA). The request described the hazard as a chronic exposure to neutron radiation during various production, maintenance and security activities. It also stated that past neutron doses have not been reported in the dose records over the past 40 years. Approximately 2,500 workers are currently employed at the PORTS and nearly 9,000 workers have been employed at the site since 1954.

Objectives

During the period between November 1996 and February 1997, area and personal neutron dose measurements were collected using thermoluminescent dosimeters and track-etch dosimeters (TLD/TEDs) to address the following objectives:

1. Determine if potential neutron exposures exist at the site.
2. Identify neutron sources.
3. Identify work areas or job titles having the greatest potential for neutron exposures.
4. Quantify neutron doses by work area or job title.

In addition, past reporting and recording practices regarding neutron doses were reviewed to determine if past doses could be reconstructed.

HHE Authority and Plant Operations

As a result of the Energy Policy Act of 1992,[1] the responsibility for the enforcement of occupational safety and health at PORTS was transferred from the Department of Energy (DOE) to the Department of Labor (DOL) and the Nuclear Regulatory Commission (NRC). This act also mandated that on July 1, 1993, certain buildings and activities of the DOE-owned gaseous diffusion plants be transferred to the United States Enrichment Corporation (USEC), a Congressionally-established, government-owned corporation that operates the United States' uranium enrichment facilities. This course of events permitted the submission of an HHE request by the workforce under provisions of the Occupational Safety and Health Act. Although several buildings remain under DOE control, they were included in this evaluation. Research applicable to an ongoing NIOSH mortality study was also conducted under a Memorandum of Understanding between DOE and the Department of Health and Human Services (DHHS)-NIOSH.[2]

Although USEC now operates the uranium enrichment facilities, the DOE maintains and operates certain buildings and activities at the PORTS. LMUS has been contracted to maintain and operate buildings for USEC regulated by the NRC and OSHA. Lockheed Martin Energy Systems, Inc. (LMES) maintains and operates buildings for the DOE under DOE orders. The buildings of interest to this HHE and their responsible agency are listed in Table I. This is an important distinction between LMUS and LMES because each company has a separate workforce and employs different dosimetry services.

Exposure vs. Dose

It is important to note that the terms *exposure* and *dose* have specific meanings when used throughout this document (see Table II). *Exposure* is used when referencing the amount of ionizing radiation present at a given point

measured in **air**. *Dose* refers to the dose equivalent or the amount of ionizing radiation absorbed in the **body** adjusted for its relative biological effectiveness. The reporting metric for this evaluation is in units of **dose** with a neutron relative biological effectiveness factor of about 10, so that appropriate comparisons can be made with the regulatory limits specified in the code of federal regulations.

BACKGROUND

Uranium

Uranium as found in nature, U_{nat}, is a radioactive element that contains a mixture of three isotopes: ^{238}U, ^{235}U, and ^{234}U (Table III). It is used primarily as fuel for commercial nuclear power plants and nuclear-powered submarines but also in nuclear weapons. In general, the ^{235}U isotope is important to these industries because it can easily undergo fission by capturing a neutron. Fission occurs when the nucleus splits, forming at least two nuclei, releasing several neutrons and a large amount of energy. Electricity is produced when heat generated from this process is transferred to a coolant that is then used to drive turbine generators. The ^{238}U isotope is also important to both industries because it can be transformed into ^{239}Pu after capturing a neutron. Plutonium-239 is another fissile element primarily used in nuclear weapons.

Even without neutron interaction, uranium changes by undergoing natural radioactive decay. The decay chains for both uranium isotopes are shown in Appendices A and B (^{238}U - Uranium Series includes ^{234}U, ^{235}U - Actinium Series). In addition, there is also a small probability that uranium will decay by spontaneous fission; i.e., uranium will fission on its own without assistance from a bombarding neutron. For example, the half-life for spontaneous fission in ^{238}U is some 6.5×10^{15} years, as compared with its radiological half-life of 4.91×10^{9} years. Because this phenomenon is so rare compared to radioactive decay, it is usually not considered a significant radiological concern. However, even this very slow spontaneous fission rate can be important in the gaseous diffusion process since large amounts of uranium are present.

Gaseous Diffusion Plants

The LMUS PORTS is one of two operating uranium enrichment production facilities in the United States: PORTS, located in Piketon, Ohio, and the Paducah Gaseous Diffusion Plant (PGDP) located in Paducah, Kentucky. Each plant uses the gaseous diffusion process to enrich uranium from the natural level of 0.71% ^{235}U to higher concentrations, which historically have ranged from 2% to greater than 97%. The LMUS PORTS has discontinued high assay ^{235}U production and currently produces a product that is between 2 to 5%, for use in fuel rods in commercial nuclear power plants. The level of enrichment is determined by physical or chemical measurements of fissionable material (^{235}U) present in the uranium.[3]

Process

Production of enriched uranium at PORTS began in late 1954. The two gaseous diffusion plants (PORTS and PGDP) have operated in a complementary mode. The Paducah facility performs the initial enrichment of uranium to about 1 to 2% ^{235}U. This material serves as a feedstock for PORTS, although the PORTS facility can also use the same feed materials that PGDP receives. The uranium is enriched by diffusing uranium hexafluoride (UF_6) through a porous material commonly called the barrier. Lighter molecules ($^{235}UF_6$) travel at a higher velocity than the heavier molecules ($^{238}UF_6$). When the mixture contacts the barrier, the lighter molecules strike the barrier and pass through it more readily than the heavier molecules. The maximum separation that can be achieved through the barrier is equal to the square root of the ratio of the weights of the gas molecules. Since the

square root of that ratio for UF_6 molecules is 1.0043, many passes through the barrier are required to reach the desired enrichment assay of $^{235}UF_6$.[4]

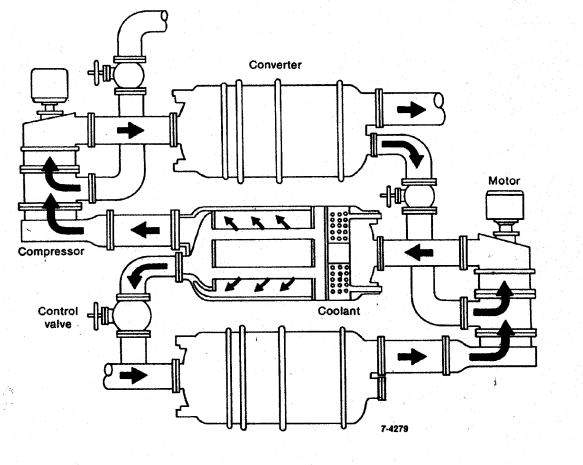

Figure 1: Stage Components

Each *stage* in the enrichment process consists of a compressor, converter (contains the barrier), and motor, (Figure 1). Between eight and 12 *stages* are linked together in series to form a *cell*. Between 10 and 20 *cells* (80 to 240 *stages*) are assembled to form a functional *unit*. These *units* are linked together to form the *cascade* for uranium enrichment. The PORTS' several thousand stages are housed in three interconnected buildings (X-333, X-330 and X-326) (Figure 2). Each cascade building has two floors, each floor covering approximately 1.5 million square feet.[5] The overall configuration results in a flow of increasingly enriched $^{235}UF_6$ toward the top of the process (X-326 building). Depleted $^{238}UF_6$ flows toward the bottom or "tails" of the process (X-333 building).

Because UF_6 is a solid at room temperature, it is delivered to and shipped from the facility as a solid in various cylinder types and sizes. The cylinders vary between small 5-inch-diameter cylinders to 14-ton cylinders to prevent an uncontrolled nuclear chain reaction, also known as a criticality, which releases potentially lethal amounts of ionizing radiation (neutrons and high energy photons).

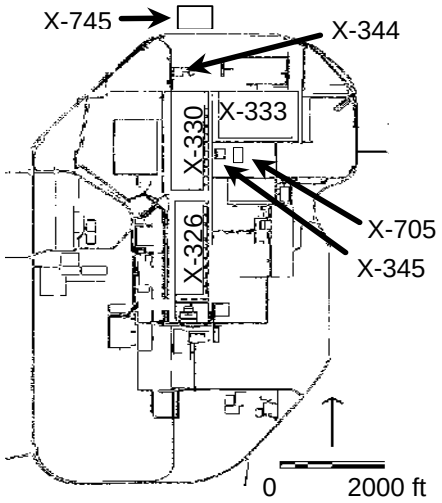

Figure 2: PORTS Facility

Major Radiation Sources

Major sources of radiation exposures at PORTS are low energy photons from ^{235}U, thorium (^{231}Th and ^{234}Th), beta particles from protactinium (^{234m}Pa), and bremsstrahlung radiation produced by the beta particles from uranium daughters and technetium (^{99}Tc) (See Appendices A and B). Other potential sources within this category but with limited exposure potential to the workforce include high energy photons from calibration sources of cesium (^{137}Cs), radium (^{226}Ra), and cobalt (^{60}Co), and machine-generated x-rays at tube potentials ranging from 70 to 200 kilovolts (kV).[6] Bremsstrahlung refers to the secondary photon radiation associated with the deceleration of charge particles (electrons) passing through matter.[3] Very low levels of gamma and bremsstrahlung radiation (0.2 to 0.1 microsieverts per hour, μSv/hr) are found throughout the process buildings. The highest levels (up to 50 μSv/hr) can be found in UF_6 feed cylinder handling areas.[6] Technetium-99 is a beta-emitting fission product introduced into the PORTS cascade from reprocessed spent reactor fuel, referred to as recycled uranium (RU). It concentrates in the top end of the enrichment process (X-326 building) because it is lighter in relation to the uranium isotopes.

Minor Radiation Sources

The minor sources of radiation exposures at PORTS are from trace amounts of the transuranic elements neptunium (^{237}Np) and plutonium (^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu). These are introduced into the enrichment process through recycled uranium. Additionally, RU contains trace amounts of uranium isotopes not found in nature, such as ^{232}U and ^{236}U. The radiological impact of these impurities is negligible in many cases. However, chemical processes that concentrate these radionuclides may require that certain radiological controls be employed. These exposures may become more common as the United States continues to increase the amount of RU processed at these facilities.[7]

Neutrons

A neutron is an elementary nuclear particle, having no electrical charge, with a mass approximately the same as that of a hydrogen atom (one electron and one proton) (Figure 3). Since neutrons carry no charge, they are not affected by the electric forces surrounding atoms and interact with the nuclei of the target material. As a result, the neutron may be either totally absorbed (captured) or significantly changed in its direction or energy.

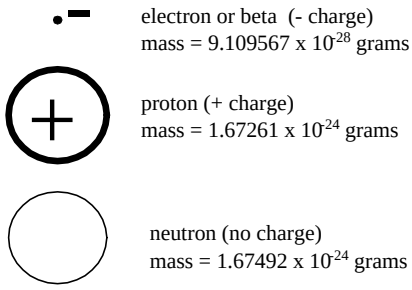

Figure 3: Parts of an Atom

The principle behind measuring neutron radiation is to use some type of conversion of the incident neutrons into secondary charged particles that can then be detected.[8] The usefulness of a target material used in this process is largely dependent on the cross-section (or probability of interaction) of that material relative to the energy of the colliding neutron. Neutron energies are usually categorized into three groups: thermal, intermediate, and fast. Thermal neutron energies (sometimes given as 0.025 electronvolts, eV) are typically considered to be neutrons with energies below the *cadmium cutoff, about 0.5 eV.* Cadmium is commonly used as a shield to differentiate thermal neutrons from higher-energy neutrons. Slow and intermediate neutrons typically range in energy levels between 0.5 eV and 100,000 eV. Fast neutrons have energies greater than 100,000 eV.[9, 10]

The dose (energy deposited per unit mass of tissue) received from neutrons is very difficult to measure accurately because of the difficulties in detecting the neutrons and characterizing their energies. In addition, neutron dosimetry presents a difficulty not encountered in electron or photon dosimetry. Neutrons produce photons once they enter the material, creating a problem of mixed-field dosimetry. To assess neutron doses from mixed fields, measurements are made using several thermoluminescent chips with varying sensitivities to neutrons and photons.[11]

Neutrons at PORTS are produced from a fission or spontaneous fission of the uranium isotopes. Neutrons can also be produced by reactions between alpha particles emitted by uranium isotopes (primarily ^{234}U) with bonded fluorine atoms.[6,12] The following nuclear reactions illustrate how neutrons could be produced at this facility:

Spontaneous Fission*

$$^{235}_{92}\mathrm{U} \rightarrow {}^{146}_{57}\mathrm{La} + {}^{87}_{35}\mathrm{Br} + \textbf{2 neutrons} + \textit{energy}$$

Fission*

$$^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{147}_{57}\mathrm{La} + {}^{87}_{35}\mathrm{Br} + \textbf{2 neutrons} + \textit{energy}$$

Interaction*

$$^{4}_{2}\alpha + {}^{19}_{9}\mathrm{F} \rightarrow {}^{22}_{11}\mathrm{Na} + \textbf{neutron} + \textit{energy}$$

*La = Lanthanum; Br = Bromine; Na = Sodium

It is important to note that the ^{235}U nucleus can fission by some 40 or so methods. Also, ^{234}U is primarily responsible for neutron production in the interaction example because it produces alpha particles (decays by alpha emission) at a rate of about 2,900 and 18,000 times faster than ^{235}U and ^{238}U, respectively.

It is clear from the physical nature and characteristics of uranium and uranium compounds that neutron exposures are most likely to occur in areas where uranium is stored (cylinder yards) or routinely handled (feed and withdrawal areas) and in areas where uranium forms deposits within the cascade. The point at which this exposure becomes a radiological concern depends on several factors, including: neutron production/generation rates, enrichment, neutron moderation factors, geometry, deposit size, detection capabilities, time of exposure, and distance from a source.

Uranium Deposits

The uranium enrichment process employed at PORTS requires that the uranium compound UF_6, be maintained in a gaseous state. However, there are four basic mechanisms by which uranium in the cascade may solidify and form a deposit: freeze-outs, inleakage, consumption, and adsorption. Freeze-outs are solidification of UF_6 due to inappropriate temperature and pressure conditions. Typically these are not a common problem and can be detected through interpretation of unusual instrument readings or equipment performance indicators. Inleakage of atmospheric moisture causes the formation of uranium oxyfluoride solids (uranyl fluoride or UO_2F_2) by water vapor reacting with the UF_6. Catastrophic failure of process equipment can cause large amounts of inleakage that can be readily detected. However, chronic leaks into the system produce deposits that may go undetected for longer periods of time. Consumption is the formation of uranium fluoride solids by UF_6 reduction reactions with cascade metals. Adsorption is the boundary layer condensation of UF_6 on internal equipment surfaces. Both consumption and adsorption occur throughout the cascade under normal operating conditions and routinely remove UF_6 from the gas phase. Together, these two mechanisms have been termed the "retained inventory effect" to account for undetected inventory losses during normal operation conditions.[13]

Neutron and gamma measurements are used as nondestructive methods to detect and quantify known uranium deposits within the cascade. Neutron measurements serve two purposes. First, they quantify the amount of material in a piece of equipment being removed from the cascade. Secondly, they determine the type of special handling required to minimize worker exposures and to prevent a criticality.[14] Neutron measurements are primarily used when the associated gamma emissions from uranium are sufficiently attenuated or shielded by equipment like compressors and heat exchangers. Gamma-ray measurements are used to supplement neutron data in assessing the size of deposits in converters and process piping and may also be used to assess the relative concentrations of ^{234}U, ^{235}U, and ^{238}U.[12]

Material balance techniques have also been employed to determine how much uranium has "fallen out" of the gaseous phase within the entire cascade. This "in-process" inventory is determined by computer calculation (using plant gauge data) and compared with the physical "book" inventory of inputs vs. outputs to obtain differences in the material balance.[12] Since neither method accounts for solidified uranium within the cascade, the difference could be used as measure of the total amount of solidified uranium within the cascade.

Criticality

A criticality occurs when, on the average, a neutron emitted by the methods described earlier causes another nucleus to fission. When this reaction becomes self-sustaining so that one fission triggers another, the phenomenon is termed a *critical chain-reaction* (Figure 4). A controlled chain-reaction occurs in nuclear reactors whereby the *rate* of fissioning is maintained after the reactor has reached

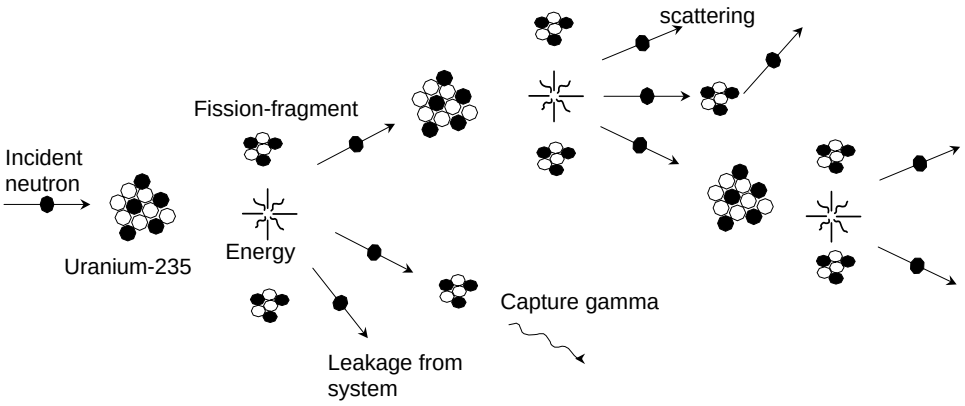

Figure 4: Simple schematic of fission chain reaction.

a stage of criticality. A reactor in which the rate of fissioning is decreasing is *sub-critical*, and one in which the rate of fissioning is increasing is *super-critical*. An atomic bomb could be described as *super-super-critical.*[15]

Four main outcomes in this chain reaction determine when a criticality has been achieved: (1) a complete loss of neutrons by escape or "leakage" from the system; (2) capture of a neutron by a fissile material (^{235}U), resulting in a reaction other than fission (such as radiative capture); (3) capture of a neutron by a non-fissile material (impurities); and, (4) capture of a neutron by a fissile material that undergoes fission. Physical and chemical characteristics as well as engineering controls must be optimized to reduce the loss of neutrons and maintain a state of criticality. The PORTS facility has been designed and operated to minimize the possibility that these factors reach the level necessary to create a critical event. As a result, there have been no critical events in the history of the facility.

"Slow Cookers"

Although PORTS has never experienced a criticality, neutrons are produced at the site. A slow buildup of uranium material within the cascade causes a slight increase in the production of neutrons. If the buildup continues without intervention, the "growing" deposit may lead to a critical or super-critical event.[16] This phenomenon of a slow build-up of uranium material that approaches criticality has been termed by the gaseous diffusion industry as a *slow cooker*. In essence, a *slow cooker* is a mass of uranium in which there is a multiplication of neutrons but at a rate below the critical threshold. *Slow cookers* are directly associated with uranium deposits which have routinely occurred at the PORTS since the plant's inception.[17, 18]

The danger associated with this phenomenon varies with the location, size, and type of deposit formed within the cascade. In general, the number of neutrons produced is proportional to the amount of uranium and the degree of enrichment. For example, an equal *number* of neutrons can be produced with either a large amount of low-enriched or depleted uranium (^{238}U) or a small amount of highly enriched uranium (^{235}U). The *energy* of the produced neutron is proportional to the percent of enrichment. Highly enriched uranium will result in more energetic neutrons. The potential neutron dose (including photon exposures) from of an unknown or unidentified *slow cooker* depends on the time of exposure, distance from the source, and the *number* and *energy* of the incident neutrons interacting with the target material (tissue).

Neutron doses specifically attributable to this phenomenon could not be addressed in this

evaluation for several reasons. First, *slow cookers* remain fixed relative to the movements of the workers within the process buildings, thereby making it very difficult to link a particular worker's dose to a specific deposit. Second, the dynamic nature of *slow cookers* makes them difficult to characterize and detect. For example, they can remain stable in size, producing a chronic low-level radiation field obscured by adjacent radiation fields, and may go undetected for long periods of time. Or they may continue to build and produce an ever increasing radiation field until they are identified, characterized, and removed from the cascade. This removal action could be completed remotely by chemical treatments or by physically removing the uranium from the cascade.

Historical Neutron Exposures

Neutron exposures have always occurred at the PORTS facility but the occupational doses have been "considered insignificant** in comparison with DOE radiation protection standards."[7] Therefore, personal neutron dosimetry was not conducted at this or any other gaseous diffusion plant in the past.[19] In the mid-1980s, neutron exposures were evaluated using Eberline "rem-balls" in areas where uranium was stored. The resulting doses were a function of enrichment and distance from the source. Highly enriched material (5-inch cylinders) produced neutron dose rates ranging from 0.03 mSv/hr (3 mrem/hr) on contact to less than 0.005 mSv/hr (0.5 mrem/hr) at a distance of 1 meter. Lower-enriched material (10-ton cylinders) produced neutron rates around 0.005 mSv/hr (0.5 mrem/hr). Based on these results and assuming that three hours was an average exposure time per work day, an "annual neutron dose equivalent" of 0.75 mSv (75 mrem) was estimated.[20] Since this is 1.5% of the radiation protection standard, 50 mSv/yr (5000 mrem/yr), the contractor determined that dosimetry was not required.[21] It is not clear from the above-referenced documents if the dose included contributions from gamma exposures. If it did not, then the annual estimate would be higher than 0.75 mSv but still below the radiation protection standard. The Health Physics Manual of Good Practices for Uranium Facilities, released in 1988 stated that "*if personnel are required to spend more than a few** hours per week in close proximity to containers of uranium fluoride compounds or if their assignments require them to spend time near storage or processing areas for large quantities** of uranium fluoride compounds, the exposure to neutrons should be evaluated.*"[7]

It wasn't until 1992 that some workers in the Radiation Calibration Facility and the Applied Nuclear Technology Department at PORTS were placed in a routine neutron dosimetry program. In October 1994, a new monitoring concept that monitored only those workers entering a Controlled or Restricted area was initiated. Simultaneously, an area monitoring program that measured radiation levels where unmonitored workers could approach without a dosimeter (building exteriors and fences surrounding posted radiation areas) was initiated. Neutron dose equivalents from the area monitoring program were unexpectedly elevated, which led to further investigations to explain the anomaly.[22] Possible reasons for the elevated results were described as conservative assumptions about the neutron energies used in the dose algorithm and the type of calibration source used to derive the algorithm [*unmoderated* ^{252}Cf (Californium), fast neutrons].

A recent neutron monitoring study conducted by the site in 1995 showed that neutron doses have been measured for workers performing activities similar to those involved in this evaluation.[23] The study monitored only Uranium Material Handlers performing various tasks in eight locations throughout the plant. Observed median quarterly neutron doses were the Feed Plant (0.05 mSv), X-344 Autoclave Area (0.07 mSv), Shipping and Receiving (0.07 mSv), Cylinder Lots (0.07 mSv), X-345 (0.03 mSv), X-744G (0.02 mSv), X-326 L Cage [below limit of detection or (LOD)], and the Burn Drum Area (0.04 mSv). The mean total dose (0.40 mSv) to

** The terms "insignificant", "few" and "large quantities" were not defined in the referenced reports.[7, 19-21]

the workers in these areas was due primarily to photon exposures, while the neutron component (≈0.05 mSv) accounted for only about 12.5%. This assumes that the dose due to internal exposures was zero. No conclusions were drawn from these data because other neutron characterization efforts that would provide more accurate information regarding neutron energies and dosimetry performance measures were underway.

Pacific Northwest Laboratories Neutron Study

In September 1995, Pacific Northwest Laboratory (PNL) in Richland, Washington, was contracted to measure occupational neutron dose rates and to determine why PORTS lithium-based dosimetry was showing higher-than-expected neutron responses.[24] A primary consideration in neutron dosimetry is the range of neutron energies to which the workers are exposed. The study conducted by PNL staff used state-of-the-art neutron detectors and spectrometers. Data were analyzed using various software codes, neutron quality factors, and energy spectra to obtain neutron dose rates.

Results from this study suggest that the average neutron energies emitted from depleted and natural uranium cylinders ranged from 210 to 360 kilo-electronvolts (keV) depending on the type of measuring technology employed (tissue-equivalent proportional counters or lithium iodide detectors with polyethylene spheres and the highest-sensitivity ^{3}He proportional counters). Slightly enriched material (2%) emitted energetic neutrons around 510 keV. Five percent enriched material emitted more energetic neutrons (770 keV). The most energetic neutrons (860 keV) were detected next to the uranium having the highest enrichment (near 97%). The range of neutron energies (210 to 860 keV) indicates that thermal neutrons (energies below 0.5 eV) are not a concern at the site.

Measurements of the neutron calibration source ^{252}Cf, using both unmoderated and deuterium oxide (D_2O)- moderated techniques, denote an average neutron energy of 1403 keV and 1306 keV, respectively. Therefore, the neutron radiation fields surrounding the PORTS cylinders had much lower energy than the fields produced by the calibration sources.[24] This may result in higher dose estimates unless the energy differential is accounted for in the dose algorithm. The PNL study concluded:

1. Routine occupational exposures to neutrons are well below the current regulatory limits specified by 10 CFR 20.[25]
2. Dose rates determined by instrumentation can be compared with the response of personal dosimeters exposed to the same neutron fields.
3. Neutron energy distributions vary with cylinder storage configurations, cylinder diameters, and uranium enrichment, which may produce different responses in personal dosimeters.
4. The typical calibration source, D_2O-moderated ^{252}Cf, used for neutron dosimetry calibrations, would not lead to accurate estimates of exposures near uranium cylinders.
5. Neutrons emitted by fission vs. (α,n) reactions could not be addressed.
6. The proper interpretation of occupational exposures depends on an accurate understanding of the energy distributions of the neutron field exposing the dosimeters.

Epidemiologic Study

In 1982, NIOSH initiated a retrospective cohort study to evaluate mortality associated with occupational chemical and radiological exposures. A report on the study findings, issued in January 1987, revealed non-statistically significant elevations in the standardized mortality ratios (SMRs) for stomach cancer and leukemia.[26] This study is currently being updated.

Neutrons were not listed as an exposure of concern at the beginning of the update study because all references to neutron exposures (verbal and written) indicated that they were not materially present at the site.[27] During this HHE, however, NIOSH learned that potential neutron exposures have been present since 1955. Unfortunately, they are not addressed in the current NIOSH study because historical neutron dose data do not exist in a format usable for

epidemiologic analysis. Currently, there are no plans to modify the current epidemiologic study except to consider the findings of this HHE when interpreting the results of any dose-response analyses.

METHODS

Background Material

Upon receipt of the HHE request, background material including historical documents about neutron exposures and past practices for neutron monitoring was requested from the site (Appendix C). Most of these materials described techniques used to identify uranium deposits within the cascade. A couple of reports provided information on neutron energy spectra and identified locations with the highest potential for neutron exposures.[24, 28] These were areas where large amounts of uranium were stored or handled (cylinder inspection, storage, filling, etc.). All of the energy spectrum data used in the HHE evaluation were based on the PNL study. NIOSH did not conduct neutron spectrum measurements; however, neutron monitoring was performed using thermoluminescent dosimeters combined with track etched dosimeters (TLD/TEDs) in selected areas and on specified personnel whose job titles suggested exposure potential.

Monitoring Selections and Dosimeters

During the November 1996 initial survey, locations for area and personnel monitoring were selected by representatives of management and the two unions. Workers in the selected job titles were given a TLD/TED badge designed to measure neutrons. The TLD/TEDs were provided by a vendor (Landauer, Inc.) accredited by the National Voluntary Laboratory Accreditation Program (NVLAP) and experienced with DOE facilities accredited by the Department of Energy Laboratory Accreditation Program (DOELAP).[29] (See NVLAP vs. DOELAP section below for further explanation). The Landauer badge, Neutrak ER, combines a TLD albedo dosimeter with an allyl diglycol carbonate-based (CR-39) technology. Neutrons above 30 to 50 keV can be detected by interactions in the CR-39 either directly or by recoil particles from the source. Lower-energy neutrons reflected from the body (albedo) are detected by the TLD component.[30] By comparing the response of these two elements, a qualitative indication of neutron energies and an estimate of the dose equivalent can be made. Thermal neutrons were not measured during this evaluation based on the findings from the PNL study.[24] In addition, neutrons at PORTS are produced at much higher energy levels than thermal energy levels.

Job titles selected for monitoring included: Uranium Material Handler, Process Operator, Health Physics Technician, Chemical Operator, and Security Guard. Table IV lists number of selected workers in each job title that agreed to participate in the HHE. Area dosimeters were placed on one-gallon polyethylene "cubitainers" filled with either 100% water (indoor measurements) or a mixture of 50% water and 50% antifreeze (outdoor measurements). The liquid-filled "cubitainers" served as tissue-equivalent phantoms. Antifreeze was deemed necessary by the investigator to prevent the solution from freezing, which might have affected neutron moderation and sensitivity of the TLD/TEDs during the winter months (November - February). Three workers agreed to serve as "field" controls and several "NIOSH" controls were employed for quality assurance purposes (see Table IV). Each dosimeter stayed in the field for approximately one calender quarter (November 5 - February 5). Then they were collected and sent to the vendor for analysis.

Evaluation of Historical Neutron Doses

In addition to performing neutron monitoring on current workers and in selected locations, an attempt was made to evaluate potential historical doses from neutron exposures by reviewing TLD chip readings from the past dosimetry programs. In early 1981, PORTS began using TLD technology to replace their film-based dosimeters as a part of their routine

monitoring program. The early film badges (1950s-1980) and the first TLD badges (1981-1990) were neither calibrated for, nor read, neutron exposures.[20] The first TLD dosimeters originally consisted of four TLD chips. Three were sensitive to penetrating beta-gamma radiation (Lithium, Li-700) and the fourth (Li-600) was sensitive to both gamma and neutron radiation. These chips were shielded by various materials to help determine the type of dose received by the workers. The ratio between the Li-600 and Li-700 chips could be used as a semi-quantitative indicator of neutron exposure. A chip ratio outside expected ranges could suggest that a chip was damaged or that a neutron exposure had occurred. Unfortunately, the past health physics practice was to assume that most, if not all, abnormal chip ratios were due to damaged chips rather than evaluate them for potential neutron exposures.

Despite past practices regarding abnormal chip ratios, a request was made to obtain historical computerized data containing chip readings from 1981 to the present.[31] These were to be reviewed to determine if certain worker groups had higher rates of abnormal ratios than other worker groups. This would provide additional information about the existence and relative degree of past neutron exposures to the workforce. However, problems were encountered in retrieving the data. First, the storage format and type of dosimetry reading equipment changed through time and would have required substantial time and resources to recover. Secondly, the older dosimetry equipment (Harshaw 2276) was a direct-reading machine and did not create a date field when the results were stored. Finally, many archive tapes had been reused, and most of the historical data was overwritten with more recent data.[32] Consequently, data available for this purpose was limited to only the most recent measurements (1992-1995). Thus, it was not feasible to reconstruct neutron exposures from previous TLD chip readings before 1992.

NVLAP vs. DOELAP

The PORTS is maintained and operated by separate contractors (LMUS and LMES) under different regulatory agencies (NRC and DOE), as identified in Table I. This introduces a level of complexity in evaluating the neutron exposures at the site since each contractor uses separate dosimetry services. The dosimetry services used by LMUS require accreditation through NVLAP. Dosimetry services through the DOE, used by LMES, require accreditation by DOELAP. The special radiological environments associated with the DOE facilities led DOE to develop and maintain a separate testing standard to provide adequate monitoring for their sites' unique radiation fields.[9, 33] Most facilities regulated by the NRC, such as commercial nuclear power plants, have predictable radiation fields and can use dosimetry services provided by any vendor accredited by NVLAP. Accreditation requirements differ between the two agencies. DOELAP only accredits DOE facilities, not commercial vendors, like NVLAP does. The differences between the two accreditation programs related primarily to calibration protocols (type of source, angular response, dosimeter location, and backscatter).[34] While DOE facilities use commercial vendors, it is the DOE facility that holds the accreditation, not the vendor. DOE facilities have not sought NVLAP accreditation since the DOE is more stringent and not subject to NRC regulation. NVLAP accreditation would incur additional costs to the sites, and there is no regulatory need unless they are also a NRC licensee, as is the case for PORTS.[29]

Currently, no resolution has been reached between the NRC and DOE regarding the use of a single dosimetry service for workers exposed to ionizing radiation at PORTS. Therefore, LMUS and LMES workers are monitored by separate dosimetry programs, accredited by NVLAP or DOELAP, respectively. This dual monitoring system adds another level of complexity to the challenge of assessing neutron exposures at the PORTS.

EVALUATION CRITERIA

NIOSH field staff employ environmental and occupational evaluation criteria for the assessment of most chemical and physical agents as a guide to the evaluation of the hazards posed by workplace exposures. These criteria are intended to suggest levels of exposure to which most workers may be exposed for a working lifetime without experiencing adverse health effects. It is, however, important to note that not all workers will be protected from adverse health effects even though their exposures are maintained below these levels. A small percentage may experience adverse health effects because of individual susceptibility, a pre-existing medical condition, and/or a hypersensitivity (allergy). In addition, some hazardous substances may act in combination with other workplace exposures, the general environment, or with medications or personal habits of the worker to produce health effects even if the occupational exposures are controlled at the level set by the criterion. These combined effects are often not considered in the evaluation criteria. Also, some substances are absorbed by direct contact with the skin and mucous membranes, and thus potentially increase the overall exposure. Finally, evaluation criteria may change over the years as new information on the toxic effects of an agent become available. NIOSH encourages the more protective criterion.

The primary sources of occupational evaluation criteria applicable to this HHE are: (1) Nuclear Regulatory Commission Standards for Protection Against Radiation, and (2) Department of Energy Occupational Radiation Protection.[25, 35] The dose limit for ionizing radiation requires that doses combined from internal (alpha) and external (beta, gamma, and neutron) exposures be below 50 millisieverts per year (5000 mrem/yr). The following section addresses the limitations associated with comparing the results from this HHE to the current regulatory limit. Although the gaseous diffusion industry is one of the lowest-exposure industries dealing with radioactive substances, historical summary statistics regarding radiation doses in this industry neither included nor addressed neutron doses.[36] Despite this limitation, it will probably remain one of the lowest-exposure industries among those dealing with radioactive substances.

RESULTS AND DISCUSSIONS

Area and Personal Neutron Measurements

Area and personal neutron doses recorded by the TLD/TEDs placed by NIOSH between November 1996 and February 1997 are listed in Tables V and VI. Two areas within Building X-326, Extended Range Product Station (ERP) and Product Withdrawal Area (PW), had measured neutron doses at or slightly above the detection limit of 0.2 mSv (20 mrem) during the monitoring period. The four locations in X-330 included the Tails Withdrawal Area, a location next to a known uranium deposit, a randomly selected location within the building, and the Low Assay Withdrawal Area (LAW). Neutrons were not detected above the detection limit at the Tails Withdrawal Area, the known uranium deposit, or at the randomly selected location. However, the known uranium deposit was removed at some time during the monitoring period, which prevented assessment of potential neutron doses near a known deposit. Neutron doses ranging between 0.4 - 0.6 mSv (40 - 60 mrem) were measured at the LAW Area. In the X-343 area, where nearly 300 storage cylinders are handled monthly, the neutron results ranged between non-detectable and 0.2 mSv. All doses at the X-345 and X-705 locations were below the detection limit. The highest neutron doses were found within the X-745-c cylinder yard maintained by the DOE; they ranged between 2.1 and 7.1 mSv in section 44 and 2.1 to 5.1 mSv in section 3.

None of the workers monitored during this evaluation received neutron doses above the minimum detection limit of 0.2 mSv. However, neutrons were measured in areas commonly occupied by workers (LAW Area and cylinder yards).

General Limitations

The results obtained from this evaluation represent only a brief period of time relative to the plant's entire history. The results from this evaluation may not fully represent past or future neutron exposure scenarios. Locations monitored during this evaluation will continue to provide a potential for future neutron exposures, depending on the amount of uranium stored, solidified, or handled in the areas. The lack of detectable neutron doses during this monitoring period **should not** be generalized in a retrospective manner nor applied to other locations or job titles. Neutron exposure potential for other areas and workers should be evaluated. Dynamic factors such as unidentified *slow cookers* or emergencies may expose workers to detectable levels of neutrons. It should also be noted that not every exposure scenario was evaluated during this HHE because several activities (removal of known uranium deposits, special decontamination activities, accidents, etc.) either did not occur or were not scheduled prior to the start of the neutron monitoring.

Area Measurement Limitations

Area neutron measurements obtained in the X-345 building (high-assay storage vaults) were limited to the lobby area within the building. The greatest potential for neutron exposures exists in the vault areas within X-345, where the special nuclear material is stored. Neutron monitoring in the vaults was prohibited due to criticality concerns associated with the use of the NIOSH phantom material. Since the lobby area was already equipped with an approved phantom material, neutron measurements were obtained there.

Variability in the area measurements obtained from the X-745-c locations suggests that dosimeter orientation to the incident neutron radiation is an important factor in determining the dose. Detection efficiency could be reduced by nearly a factor of three, depending on the neutron angle of incidence to the TLD/TEDs.[37] This measurement variability could be a concern if a worker is performing activities near a suspected neutron source for an extended period.

Comparing HHE Results to the Regulatory Limit

The results reported in this HHE represent only doses from neutron exposures. The regulatory limit is based on a "total" dose concept that also incorporates doses from internal (alpha) and other external (beta and gamma) exposures. Comparing the results of the neutron measurements with the regulatory limit should be done with the understanding that only a fraction of the "total" dose is represented in these results. For example, the LAW Area results ranged between 0.4-0.6 mSv (40 - 60 mrem) during the quarter. This value would represent a worker's neutron dose if he or she spent 24 hours per day for 90 days in this work area. Doses from other internal or external exposures were not obtained; however, applying a conservative assumption that neutrons account for about 12.5 percent of the total dose (assuming zero internal dose), a worker could receive a total radiation dose between 3.2 - 4.8 mSv (320 - 480 mrem) during the quarter. This represents the maximum dose a worker could receive in this radiation area, assuming operating conditions remain constant. A more realistic estimate of a worker's dose would be to adjust the time spent in the radiation area. An adjusted result using three hours per work day as an average time spent in the radiation area is shown in equation 1.

$$\frac{40mrem}{1qtr} x \frac{1qtr}{90days} x \frac{1day}{24hours} x \frac{3hours}{1workday} x \frac{65workdays}{1qtr} = 3.6\frac{mrem}{qtr} \quad (1)$$

A neutron dose of 3.6 mrem would imply a total dose of about 29 mrem (3.6 / 0.125 = 28.8) from all external sources if neutrons account for 12.5 percent of the total dose as described earlier. This value of a total dose could then be directly compared with the regulatory limit (assuming there is no internal dose component). Continuing with the 12.5 percent assumption, it would take a total external dose of about 160 mrem to measure neutrons at the TLD/TED detection limit of 20 mrem (20 / 0.125 =

160). Since most external doses due to gamma exposures are below 160 mrem, it would be unlikely that neutrons could be detected at PORTS and may explain why all the personal TLD/TED measurements were below the limit of detection.

Historical Health Physics Practices

In an effort to reconstruct past neutron exposures, the historical health physics monitoring and reporting practices were reviewed. LMUS and union personnel indicated that abnormal chip ratios and high doses (above 2.7 rem) were routinely assumed to be due to equipment failure ("bad badges") and little effort was made by the Health Physics Department to investigate such doses. The 2.7-rem dose supposedly occurred in the early 1970s during the removal of a uranium deposit in the X-326 building (high-assay). However, no report was found in reviewing the Health Physics Exposure Investigation Reports regarding this event. In addition, no such dose was found in reviewing the computerized Health Physics historical data provided by the site to NIOSH in support of the current epidemiologic study. Past recording and reporting activities applied to high doses were provided as reasons for the lack of historical documents and missing data. Recording decisions regarding high doses were based on the philosophy that doses of this size were very unlikely when compared with past doses reported and recorded at the site. Therefore, equipment failure was provided as the reason for the abnormal dose, and the recorded dose was entered as something other than the measured value. Official documentation of this policy for reducing assessed doses could not be found, however. A measured dose of this size may be possible if the exposure occurred near a highly enriched uranium deposit. The *slow cooker* phenomenon could explain doses in this range.

In addition, this review found that background measurements used to correct personal results have changed throughout time.[32] Depending on the type of dosimetry system used, background was handled in one of three ways: it was calculated using statistics, manually entered into the dosimetry algorithm, or determined from badges in or near the working areas. All these methods have certain limitations. The latter may **not** represent true background exposures (especially if these locations were in elevated radiation areas). Another issue regarding reporting and recording practices involves doses that could not be linked to individuals. A computerized account, setup to store these "unlinkable" doses, is commonly called the *bucket dose* account.[38] A cursory review of this account indicated that several person-rem could not be assigned to individual workers or visitors. Both approaches (background issues and *bucket doses*) reduce the reportable doses and will eventually lead to an artificially low dose history for the facility.

CONCLUSIONS

This evaluation showed that a potential chronic low-level neutron exposure exists at this site where uranium is stored, handled, or solidified within the cascade. Areas most likely associated with neutron exposures include the Feed and Withdrawal areas, cylinder storage yards, and places where uranium deposits are formed within the cascade. Job titles most likely associated with potential neutron exposures would be those involving routine tasks in potential neutron areas (listed in Table IV). Area neutron doses ranged from less than the detection limit (0.2 mSv) to 7.1 mSv and varied with the amount of uranium present, its enrichment level, geometric configuration, and time spent near the source. While the area measurements confirmed the presence of a chronic low-level exposure to neutrons, all personal doses were below the limit of detection. Recent neutron monitoring results conducted by the site have shown reportable neutron doses. Historical health physics programs (1954 - 1992) neither calibrated nor monitored for neutron exposures. Therefore, potential neutron doses have not been included in the workers dose histories. Data from this evaluation were based on a small sample size and may reflect specific production and seasonal conditions during the 3-month period.

The current dosimetry programs at PORTS for LMUS and LMES workers are NVLAP- and DOELAP- accredited, respectively, and now account for potential neutron doses. Each contractor uses and calibrates dosimeters that are virtually identical. Although differences exist in the specific dose algorithms, it is not a substantial problem because of the general difficulty associated with assessing neutron doses.

RECOMMENDATIONS

The following recommendations are based on observations made during the survey and document reviews. They are intended to help ensure the safety and health of the workforce. These recommendations stem from the present understanding of the workers' occupational exposures and potential health effects associated with these exposures.

1. The area TLDs used by LMES (DOE contractor) should be used with an appropriate phantom material to monitor neutron exposures in the X-345 vault areas properly.

2. To ensure maximum efficiency in detecting neutrons, workers who are likely to be exposed to neutrons should be informed about the proper positioning of the TLD and its angular dependence in detecting incident neutrons.

3. The document entitled "D_2O-Moderated Californium-252 Neutron Calibration Factor (K_{nd}) Determination" dated August 17, 1995, should be revised. A minor error in the calculation should be corrected. The Mean Net Test Response calculation used the Mean *Gross* Test Signals instead of the Mean *Net* Test Signals as referenced in the text.[39]

4. The linkage issues regarding the "bucket dose" account should be reviewed and corrected to improve record keeping and reporting activities. Where possible, the "bucket" doses should be assigned to individual workers.

5. Archive tapes should not be recycled to facilitate future dose reconstruction efforts for compliance or epidemiologic purposes.

6. Area monitoring should continue to be performed in areas where uranium is routinely stored or handled to characterize potential neutron exposures better. In addition, efforts should be taken to evaluate potential neutron doses associated with known uranium deposits within the cascade.

7. Past maintenance activities and personnel involved in physically removing uranium deposits should be evaluated to provide better insight on the doses attributable to the *slow cooker* phenomenon.

8. Administrative changes or decisions regarding issues in the health physics dosimetry program (doses below the limit of detection, abnormal chip ratios, investigative reports, etc.) should be better documented and routinely reported to the workforce to educate, inform, and solicit questions about how the changes or decisions will affect their dose records.

ABBREVIATIONS AND TERMS

CFR	Code of Federal Regulations
DHHS	Department of Health and Human Services
DOE	Department of Energy
DOELAP	Department of Energy Laboratory Accreditation Program
DOL	Department of Labor
ERP	Extended Range Product
HHE	Health Hazard Evaluation
LAW	Low Assay Withdrawal
LMUS	Lockheed Martin Utility Services

LOD	Limit of Detection
LMES	Lockheed Martin Energy Services
NIOSH	National Institute for Occupational Safety and Health
NRC	Nuclear Regulatory Commission
NVLAP	National Voluntary Laboratory Accreditation Program
OCAW	Oil, Chemical and Atomic Workers Union International
PGDP	Paducah Gaseous Diffusion Plant
PNL	Pacific Northwest Laboratories
PORTS	Portsmouth Gaseous Diffusion Plant
PW	Product Withdrawal Area
TEPC	Tissue Equivalent Proportional Counter
TLD	Thermoluminescent Dosimeter
OSHA	Occupational Safety and Health Act
RU	Recycled Uranium
Sv	Sievert
UPGWA	United Plant Guard Workers of America
USEC	United States Enrichment Corp.

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Table I
USEC and DOE Portsmouth Facilities Selected for Monitoring
Portsmouth Gaseous Diffusion Plant, Piketon, Ohio (HETA 96-0198-2651)

Facility	Description	LMUS USEC (NRC)	LMES DOE
X-326	Process Building (Highly Enriched U*)	X	
X-330	Process Building	X	
X-333	Process Building (Depleted U)	X	
X-344-A	UF_6* Sampling Building	X	
X-344-B	Maintenance Storage Building	X	
X-705	Decontamination Building	X	
X-345	SNM* Storage Building		X
X-745	Cylinder Storage Yards		X

* SNM = Special Nuclear Material
U = Uranium
UF_6 = Uranium Hexafluoride

Table II
Radiological Units[#]
Portsmouth Gaseous Diffusion Plant, Piketon, Ohio (HETA 96-0198-2651)

Quantity	Name	Symbol	Units
Exposure	coulomb per kilogram (roentgen)	 (R)	$C\ kg^{-1}$ ($2.58 \times 10^{-4}\ C\ kg^{-1}$)
Dose Equivalent	sievert (rem)	Sv (rem)	$J\ kg^{-1}$ (10^{-2} Sv)

[#] Old units are in brackets.

Table III
Isotopes Present in Natural Uranium*
Portsmouth Gaseous Diffusion Plant, Piketon, Ohio (HETA 96-0198-2651)

Isotope	Abundance (%)	Half-life (Years)
^{238}U	99.2739 ± 0.0007	4.46×10^{9}
^{235}U	0.7204 ± 0.0007	7.04×10^{8}
^{234}U	0.0057 ± 0.0002	2.45×10^{5}

* Source: Shleien, G. The Health Physics and Radiological Health Handbook. Revised Edition, Scinta, Inc. Silver Spring, MD. 1992.

Table IV
Neutron Monitoring Selections
Portsmouth Gaseous Diffusion Plant, Piketon, Ohio (HETA 96-0198-2651)

Job Titles	Number
Chemical operators	11
Health physics technicians	5
Laborers (painters/scrapers)	5
Maintenance	1
Process operators	12
Security guards	5
Uranium material handlers	18
Personal measurements	57
Area measurements	33
Field controls (HP, 2 Union Reps)	3
NIOSH controls	8
Total Measurements	101

Table V
Area Neutron Measurements
Portsmouth Gaseous Diffusion Plant, Piketon, Ohio (HETA 96-0198-2651)
November 1996 - February 1997

Area or Control	Buildings (Area)	Location/Comments	TLD/TED Number[†]	Dose (mSv)[‡]
Area	X-326	ERP (Dynamics St. #2)	53	0.20
		ERP (Dynamics St. #2)	54	0.20
		ERP (Dynamics St. #2)	55	0.40
		PW (T-57-8-3 Bed #3)	60	0.20
		PW (T-57-8-3 Bed #3)	61	0.20
		PW (T-57-8-3 Bed #3)	66	0.20
Area	X-330	Tails	73	<0.20
		Tails	74	<0.20
		Tails	75	<0.20
		Deposit; dd-4; 29AB-1	57	<0.20
		Deposit; dd-4; 29AB-1	63	<0.20
		Deposit; dd-4; 29AB-1	69	<0.20
		G33; 29-3-7-7 (randomly selected)	56	<0.20
		G33; 29-3-7-7 (randomly selected)	62	<0.20
		G33; 29-3-7-7 (randomly selected)	68	<0.20
		LAW (near eye wash)	71	0.60
		LAW (near eye wash)	72	0.40
		LAW (near eye wash)	78	0.60
Area	X-343	Typical Movement (300 cylinder/month)	59	<0.20
		Typical Movement (300 cylinder/month)	65	<0.20
		Typical Movement (300 cylinder/month)	67	0.20
Area	X-345	Behind Phantom #5 on wall	37	<0.20
		Behind Phantom #5 on wall	40	<0.20
		Behind Phantom #5 on wall	42	<0.20
Area	X-705	Portal	95	<0.20
		Portal	96	<0.20
		Portal	98	<0.20

Table V (continued)
Area Neutron Measurements
Portsmouth Gaseous Diffusion Plant, Piketon, Ohio (HETA 96-0198-2651)
November 1996 - February 1997

Area or Control	Buildings (Area)	Location/Comments	TLD/TED Number[†]	Dose (mSv)[‡]
Area	X-745-c	DOE Lot; 11,200; 2-3%; row 22-23 Sec. 44	47	4.20
		DOE Lot; 11,200; 2-3%; row 22-23 Sec. 44	52	2.10
		DOE Lot; 11,200; 2-3%; row 22-23 Sec. 44	76	7.10
		DOE Lot; 11,200; 2-3%; row 20-21 Sec. 3, heel	58	2.10
		DOE Lot; 11,200; 2-3%; row 20-21 Sec. 3, heel	64	5.10
		DOE Lot; 11,200; 2-3%; row 20-21 Sec. 3, heel	70	3.20
Controls		Stayed at NIOSH	0	<0.20
		Stayed at NIOSH	1	<0.20
		Stayed at NIOSH	2	<0.20
		Stayed at NIOSH	92	<0.20
		Stayed at NIOSH	93	<0.20
		Stayed at NIOSH	94	<0.20
		Stayed at NIOSH	99	<0.20
		Stayed at NIOSH	100	<0.20

[†] TLD/TED numbers provided only for reference purposes with sample locations.

[‡] Deep dose equivalent applies to external whole-body exposures and is the dose equivalent at a tissue depth of 1 cm (1,000 mg/cm^2). Dose equivalents for the monitoring period below the limit of detection are indicated by <0.20. All fast and moderate energy neutron dosimeters have a minimum reporting value of 0.20 mSv (20 mrem). A neutron quality factor of 10 has been applied to the dose estimate.

Table VI
Personal Neutron Dosimetry Results
Portsmouth Gaseous Diffusion Plant, Piketon, Ohio (HETA 96-0198-2651)
November 1996 - February 1997

Job Title	Dept.	Buildings (Area)	Comments	TLD/TED Number[†]	Dose (mSv)[‡]
Chemical Operators	771	X-705	Recovery	3	<0.20
	791	X-344, X-345, X-744-g	Cylinder Lots	5	<0.20
	771	X-705		7	<0.20
	771	X-705	Recovery	8	<0.20
	771	X-705	Small Parts	9	<0.20
	771	X-705	Small Parts	10	<0.20
	791	X-344, X-345, X-744-g	Cylinder Lots	11	<0.20
	771	X-705		13	<0.20
	771	X-705	Tunnel	15	<0.20
	771	X-705	Small Parts	17	<0.20
	721	X-326	Misc.	45	<0.20
Heath Physics Techs.	300	X-344, X-343, X-342		22	<0.20
	300	X-705	HP coverage in building	82	<0.20
	300	X-705	HP coverage in building (shift work)	83	<0.20
	300	X-343	HP coverage in building	85	<0.20
	300	X-705	HP coverage in building	86	<0.20
Laborers	147	Cylinder Yards	Paint and Scrap in yards (20 hrs/wk)	77	<0.20
	147	Cylinder Yards	Paint and Scrap in yards (20 hrs/wk)	79	<0.20
	147	Cylinder Yards	Paint and Scrap in yards (20 hrs/wk)	80	<0.20
	147	Cylinder Yards	Paint and Scrap in yards (20 hrs/wk)	81	<0.20
	147	Cylinder Yards	Paint and Scrap in yards (20 hrs/wk)	84	<0.20

Table VI (continued)
Personal Neutron Dosimetry Results
Portsmouth Gaseous Diffusion Plant, Piketon, Ohio (HETA 96-0198-2651)
November 1996 - February 1997

Job Title	Dept.	Buildings (Area)	Comments	TLD/TED Number[†]	Dose (mSv)[‡]
Maintenance	469	X-326	General Activities	39	<0.20
Process Operators	720	X-333	Cold Recovery	23	<0.20
	730	X-330	Unit Operator	33	<0.20
	730	X-330	Tails Withdrawal	34	<0.20
	740	X-326	Relief	38	<0.20
	740	X-326	Product Withdrawal (PW)	41	<0.20
	720	X-333	ACR Low Assay Withdrawal Utility	43	<0.20
	730	X-330	Tails Withdrawal	44	<0.20
	740	X-326	Rover	46	<0.20
	720	X-333	Low Assay Withdrawal Operator	48	<0.20
	730	X-330	Unit Operator (tails env.)	49	<0.20
	740	X-326	Extended Range Product Station	50	<0.20
	740	X-326	Product Withdrawal (PW)	51	<0.20
Security Guards	152	X-326, X-705, X-345		14	<0.20
	151	X-326	Product Withdrawal	36	<0.20
	152	X-326, X-705	Rotation P-12	89	<0.20
	152	X-326, X-345	Rotation P-12 - 705	90	<0.20
	152	X-345, X-705	Rotation P-12	91	<0.20

Table VI (continued)
Personal Neutron Dosimetry Results
Portsmouth Gaseous Diffusion Plant, Piketon, Ohio (HETA 96-0198-2651)
November 1996 - February 1997

Job Title	Dept.	Buildings (Area)	Comments	TLD/TED Number†	Dose (mSv)‡
Uranium Material Handlers	791	X-344, X-745-c, X-745-e		4	<0.20
	791	X-344	Cylinder Lots (movements, inspect, staging)	6	<0.20
	791	X-344	Cylinder Lots	12	<0.20
	791	X-344, X-745-c, X-745-e		16	<0.20
	791	X-326	L-Cage	18	<0.20
	791	X-744-G	Warehouse Storage	19	<0.20
	791	X-344	Autoclave	20	<0.20
	791	X-344	Autoclave	21	<0.20
	791	X-344	Shipping and Receiving	24	<0.20
	791	X-344	Autoclave	25	<0.20
	791		DOE and USEC Lots (mostly UESC)	26	<0.20
	791	X-344, X-744-g		27	<0.20
	791	X-344	Shipping and Receiving	28	<0.20
	791	X-744-g	Pick-up and delivery of cylinders, oxides, etc.	29	<0.20
	791	X-344	Autoclave	30	<0.20
	791	X-344	Autoclave	31	<0.20
	791	X-344	Cylinder Lot X-745-b, misc.	32	<0.20
	791	X-345	Vault	35	<0.20
Controls	300	All	Safety Representative	87	<0.20
		All	Health Physics Tech.	88	<0.20
		All	Safety Representative	97	<0.20

† TLD/TED numbers provided only for reference purposes with sample locations.
‡ Deep dose equivalent applies to external whole-body exposures and is the dose equivalent at a tissue depth of 1 cm (1,000 mg/cm^2). Dose equivalents for the monitoring period below the minimum reportable quantity are indicated by <0.20. All fast and moderate energy neutron dosimeters

have a minimum reporting value of 0.20 mSv (20 mrem). A neutron quality factor of 10 has been applied to the dose estimate.

Appendix A
Uranium Decay Series, ^{238}U (4n+2)†

Nuclide§	Half-Life	Major Radiation Energies (MeV) and Intensities‡					
		α		β		γ	
		MeV	%	MeV	%	MeV	%
$^{238}_{92}U$	4.468×10^9 y	4.15 4.20	22.9 76.8			0.0496	0.07
↓							
$^{234}_{90}Th$	24.1 d			0.076 0.095 0.096 0.1886	2.7 6.2 18.6 72.5	0.0633 0.0924 0.0928 0.1128	3.8 2.7 2.7 0.24
↓							
$^{234m}_{91}Pa$	1.17 m			2.28	98.6	0.766 1.001	0.207 0.59
↓							
99.87% $^{234}_{91}Pa$ ↓	6.7 h			22 βs E Avg = 0.224 Emax = 1.26		0.132 0.570 0.883 0.926 0.946	19.7 10.7 11.8 10.9 12.0
0.13% $^{234}_{91}Pa$ IT ↓							
$^{234}_{92}U$	244,500 y	4.72 4.77	27.4 72.3			0.053 0.121	0.12 0.04
↓							
$^{230}_{90}Th$	7.7×10^4 y	4.621 4.688	23.4 76.2			0.0677 0.142 0.144	0.37 0.07 0.045
↓							
$^{226}_{88}Ra$	1600 ± 7 y	4.60 4.78	5.55 94.4			0.186	3.28
↓							
$^{222}_{86}Rn$	3.823 d	5.49	99.9			0.510	0.078
↓							
$^{218}_{84}Po$	3.05 m	6.00	~100	0.33	0.02	0.837	0.0011
↓							
99.98% $^{214}_{82}Pb$ ↓	26.8 m			0.67 0.73 1.03	48.0 42.5 6.3	0.2419 0.295 0.352 0.786	7.5 19.2 37.1 1.1
0.02% ↓							
$^{218}_{85}At$ ↓	2 s	6.66 6.7 6.757	6.4 89.9 3.6			0.053	6.6
$^{214}_{83}Bi$ ↓	19.9 m	5.45 5.51	0.012 0.008	1.42 1.505 1.54 3.27	8.3 17.6 17.9 17.7	0.609 1.12 1.765 2.204	46.1 15.0 15.9 5.0

Appendix A (continued)
Uranium Decay Series, ^{238}U (4n+2)†

Nuclide§	Half-Life	Major Radiation Energies (MeV) and Intensities‡					
		α		β		γ	
		MeV	%	MeV	%	MeV	%
99.979 % $^{214}_{84}Po$	164 µs	7.687	100			0.7997	0.010
0.021% ↓ $^{210}_{81}Tl$	1.3 m			1.32 1.87 2.34	25.0 56.0 19.0	0.2918 0.7997 0.860 1.110 1.21 1.310 1.410 2.010 2.090	79.1 99.0 6.9 6.9 17.0 21.0 4.9 6.9 4.9
$^{210}_{82}Pb$	22.3 y	3.72	0.000002	0.016 0.063	80.0 20.0	0.465	4.0
$^{210}_{83}Bi$	5.01 d	4.65 4.69	0.00007 0.00005	1.161	~100		
~100% $^{210}_{84}Po$	138.378 d	5.305	100			0.802	0.0011
0.00013% ↓ $^{206}_{81}Tl$	4.20 m			1.571	100	0.803	0.0055
$^{206}_{82}Pb$	Stable						

y = Year
d = Day
h = hour
m = minute
s = second
µs = microsecond (10^{-6} s)

α = alpha decay
β = beta decay
γ = gamma decay
IT = Internal transition
MeV = million electron volts

† This expression describes the mass number of any member in this series, where n is an integer. For example: ^{206}Pb (4n+2)...4(51) + 2 = 206.

‡ Intensities refer to percentage of disintegrations of the nuclide itself, not to original parent of series. Gamma %s in terms of observable emissions, not transitions.

§ Shaded areas represent the major sources of radiation exposure at the PORTS along with technetium-99, cesium-137 and machine-generated X-rays.

Appendix B
Actinium Decay Series, ^{235}U (4n+3)†

Nuclide§	Half-Life	Major Radiation Energies (MeV) and Intensities‡					
		α		β		γ	
		MeV	%	MeV	%	MeV	%
$^{235}_{92}U$ ↓	7.038 x 10^8 y	4.2 - 4.32 4.336 4.398 4.5-4.6	10.3 17.6 56 11.3			0.1438 0.163 0.1857 0.205	10.5 4.7 54 4.7
$^{231}_{90}Th$ ↓	25.5 h			0.205 0.287 0.304	15 49 35	0.0256 0.0842	14.8 6.5
$^{231}_{91}Pa$ ↓	3.276 x 10^4 y	4.95 5.01 5.029 5.058	23 25.6 20.2 11.1			0.0274 0.2837 0.300 0.3027 0.330	9.3 1.6 2.3 4.6 1.3
$^{227}_{89}Ac$ ↓	21.77 y	4.94 4.95	0.53 0.66	0.019 0.034 0.044	10 35 54	0.070 0.100 0.160	0.017 0.032 0.019
98.62% $^{227}_{90}Th$ ↓	18.718 d	5.757 5.978 6.038	20.2 23.3 24.4			0.050 0.236 0.300 0.304 0.330	8.5 11.2 2.0 1.1 2.7
1.38% ↓ $^{223}_{87}Fr$ ↓	21. 8 m	5.44	~0.006	1.15	~100	0.050 0.0798 0.2349	34.0 9.2 3.4
$^{223}_{88}Ra$ ↓	11.43 d	5.607 5.716 5.747	24.1 52.2 9.45			0.144 0.154 0.269 0.324 0.338	3.3 5.6 13.6 3.9 2.8
$^{219}_{86}Rn$ ↓	3.96 s	6.425 6.55 6.819	7.4 12.1 80.3			0.271 0.4018	9.9 6.6
$^{215}_{84}Po$ ↓	1.78 ms	7.386	~100	0.74	~0.00023	0.4388	0.04

Appendix B (continued)
Actinium Decay Series, ^{235}U (4n+3)†

Nuclide§	Half-Life	Major Radiation Energies (MeV) and Intensities‡					
		α		β		γ	
		MeV	%	MeV	%	MeV	%
~100% $^{211}_{82}Pb$	36.1 m			0.26 0.97 1.37	4.8 1.4 92.9	0.405 0.427 0.832	3.0 1.38 2.8
0.00023% $^{215}_{85}At$	~0.1 ms	8.026	~100			0.404	0.047
$^{211}_{83}Bi$	2.14 m	6.28 6.62	16 84	0.579	0.27	0.351	12.7
0.273% $^{211}_{84}Po$	0.516 s	7.42	98.9			0.570 0.898	0.54 0.52
99.73% $^{207}_{81}Tl$	4.77 m			1.42	99.8	0.897	0.24
$^{207}_{82}Pb$	stable						

y = Year
d = Day
h = hour
m = minute
s = second
μs = microsecond (10^{-6} s)

α = alpha decay
β = beta decay
γ = gamma decay
IT = Internal transition
MeV = Million electron Volts

† This expression describes the mass number of any member in this series, where n is an integer. For example: ^{207}Pb (4n+3)...4(51) + 2 = 207.

‡ Intensities refer to percentage of disintegrations of the nuclide itself, not to original parent of series. Gamma %s in terms of observable emissions, not transitions.

§ Shaded areas represent the major sources of radiation exposure at the PORTS along with technetium-99, cesium-137 and machine-generated X-rays.

Appendix C
Requested Background Documentation

Number	Date	Author	Title
GAT-NM-137	06/23/86	Boyd, D.E.	Charac. of Process Holdup Material ...
GAT-S-56	04/20/86	Bassett, A.C.	Thermoluminescent Dosimetry Response & Calibration
GAT-S-58	01/22/86	Ruggles, D.J.	TLD Error Analysis
GAT-S-54	11/20/85	Bassett, A.C.	TLD Program Processing Proc's Harshaw 2276 ver BGX1
GAT-S-49	06/28/85	Bassett, A.C.	Calibration of TLD Albedo Neutron Dosimeters
GAT-T-866	09/08/61	Baker, D.D.	The Use of Radioactivity to Determine the Uranium ...
POEF-T-3498	09/14/88	Van Meter, C.J.	Ports. Deposit Detection Program: ..TSA Team Revision ...
POEF-T-3452	06/11/87	Lewis, D.D.	..Neutron Detectors..Uranium Deposit..In Cascade
GAT-DM-1099	07/27/66	Feuerbacher, J.L.	Use of a Neutron Probe for Assay Monitoring
GAT-DM-1085	10/20/65	Feuerbacher, J.L.	Neutron Probe Monitoring for U-235 Assay of UF6 Be ...
GAT-DM-1017	10/17/62	Feuerbacher, J.L.	Neutron Probe Readings for Safe Batches at Various ...
GAT-DM-833	04/25/60	Feuerbacher, J.L.	Nuclear Hazards Consideration for a Storage Area ...
GAT-CM-758	06/01/59	Feuerbacher, J.L.	A Guide to Operations when checking for Uranium Deposits ...

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