

THE RISKS OF MAKING NUCLEAR WEAPONS

*A Review of the Health and Mortality Experience of
U.S. Department of Energy Workers*

by

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THE DEPARTMENT OF ENERGY WORKER HEALTH STUDIES

Summary

Background

The Department of Energy (DOE) occupational epidemiological studies constitute one of the world's largest and most extensive follow ups of people exposed to low-level ionizing radiation and other substances. The studies were initiated 36 years ago and cover some 600,000 people who worked for federal contractors at industrial and research sites. These workers helped produce tens-of-thousands of nuclear weapons for the United States. Many were followed for more than 50 years when the first nuclear weapons were made during World War II. From the very beginning, it was recognized that the risks posed to nuclear weapons workers over time were not well understood. Dr. Robert Stone, the head of the Health Division of the Manhattan Project, noted that worker radiation protection "...rested on rather poor experimental evidence." He concluded, "*The whole clinical study of the personnel is one vast experiment. Never before has so large a collection of individuals been exposed to so much irradiation.*"¹

Beginning in the mid 1970's, the DOE worker studies engendered considerable controversy, in large part because of concerns over DOE's conflict-of-interest as an employer. In 1990, as a result of Congressional pressure and a growing lack of public trust, the DOE entered into a formal agreement with the Department of Health and Human Services to manage and conduct DOE worker health studies paid for by the Department of Energy. Since that time, these studies were obscured from public attention and went unappreciated. This all changed when the Secretary of Energy, Bill Richardson, announced on July 14, 1999 that the Clinton Administration would seek to establish a federal compensation program for sick Energy Department contract employees.

Recently, the Department of Energy compiled a selected group of health studies of Department of Energy contractor employees from the most recent editions of published articles and unpublished technical reports. Additional recent published studies were obtained from peer-reviewed scientific journals. The following review analyzed twenty-seven studies of workers at DOE sites and nuclear sites in the United Kingdom and Canada. They are mostly retrospective mortality studies where workers were followed for the duration of their employment and to their deaths. Exposure data included exposures to external penetrating radiation, internal depositions of radioactivity and other non-radioactive substances. Worker death rates were compared with those of the U.S. general public, with other workers within the same facilities, and workers at other nuclear facilities. Case-control studies were done where cancer cases were matched with

¹ Catherine Caufield., *Multiple Exposures: Chronicles of the Radiation Age*, Harper and Row, (1989), pp. 48,50.

the health outcomes of unexposed workers. Several worker populations were combined for the purpose of aggregate analyses. Several studies performed analyses to determine dose-response relationships between radiation exposure and the risk of dying from cancers.

Study Findings

All told, workers at fourteen DOE facilities were found to have increased risks of dying from various cancers and nonmalignant diseases. They include:

- The Hanford nuclear materials production site in Washington.
- The Oak Ridge National Laboratory in Tennessee.
- The Oak Ridge Tennessee Eastman Electromagnetic Separation facility (TEC).
- The Oak Ridge Y-12 weapons facility.
- The Oak Ridge K-25 Gaseous Diffusion Plant.
- The Feed Materials Production Center in Fernald, Ohio.
- The Los Alamos National Laboratory in New Mexico.
- The Linde Air Products uranium processing operation in New York.
- The Mallikrodt Chemical Works in Missouri.
- The Mound Laboratory in Ohio.
- The Rocky Flats facility in Colorado.
- The Savannah River Site in South Carolina.
- The Rocketdyne/Atomic International Facility in California.
- The Lawrence Livermore National Laboratory in California.

The studies show, with some exceptions, that DOE workers have an overall lower death rate than the US population and thus, exhibit a "healthy worker effect." Occupational studies have shown that workers frequently exhibit a lower risk of dying from all causes than the general public. This phenomenon is due to pre-employment health screening, higher socioeconomic status, and better access to health care. General population mortality data includes the elderly, poor and sick people. Despite the "healthy worker effect," DOE studies show that workers at several facilities have statistically significant excess deaths from specific cancers. A few studies with younger work forces, like the Portsmouth Gaseous Diffusion Plant in Ohio, exhibited excess deaths that were not statistically significant.

When internal comparisons were done that account for the "healthy worker effect," type and level of exposure, age, and other factors, cancers among DOE workers in several studies tended to rise with increasing doses of radiation. Several studies found significant dose-response correlations with exposure to ionizing radiation. Some multiple facility studies found a positive dose-response correlation of an occupational dose to radiation and deaths from cancers, while others found little evidence to support a correlation. Several referenced studies done of British nuclear workers also found excess risks of cancer related deaths and a positive correlation with radiation doses.

Workers who received more extensive radiation monitoring tend to show more pronounced correlations between excess deaths from cancer and radiation exposure. This appears to be the case for the Oak Ridge National Laboratory, Hanford and the Savannah River Site, where personnel radiation monitoring was extensive. At several DOE facilities, radiation dosimetry was not accurate or complete. For instance, exposures to more dangerous radioisotopes such as plutonium and other fission products from recycled uranium processed at several DOE facilities were not considered in studies of the uranium plants that handled these materials. Several sites had sparse and infrequent personnel monitoring for several years. For instance, the vast majority of workers at the Oak Ridge Gaseous Diffusion Plant were not measured for external radiation until 1975. Prior to 1960 the majority of workers at Oak Ridge Y-12 weapons plant also were not monitored for external radiation.

Of particular interest are studies of DOE uranium processing workers which exhibit an absence of a healthy worker effect and show increased risks of dying from malignant and nonmalignant respiratory and kidney diseases. Cancers of the immune system, such as blood forming and lymph organs, many of which are considered to be radiogenic, were found in ten studies reviewed. Cancers not previously assumed to be associated with radiation exposure such as Hodgkin's Disease and prostate cancer were found in excess and have significant dose-response correlations. Also, several studies indicate that the risk of excess cancers, following radiation exposure, increases after the age of 45 years. This suggests that older workers may be more sensitive to cancer induction from radiation.

The debate over the nature and extent of the risk of dying of radiation-induced cancers is clearly reflected in these studies. Some studies show that radiation may be a generalized carcinogen and not limited to causing certain radiogenic cancers. Other studies suggest that radiation risks may be substantially greater than official assumptions based on extrapolations from high dose studies, principally the Japanese atomic bomb survivors. By contrast, other studies report little evidence of a dose-response effect. These studies affirm official risk estimates and show radiation risks, in some instances, are limited to a small number of radiogenic cancers. Despite these disagreements, there appears to be general agreement that DOE workers are experiencing excess deaths following radiation exposure.

Individual DOE Facilities

Hanford, Washington—Increased risks of dying from all cancers were reported with a positive correlation with occupational dose (Study Nos. 1 and 3). Another study found little evidence of a positive correlation between radiation exposure and excess mortality. This study found cancer of the pancreas and Hodgkin's Disease (cancer of the lymph nodes) have a positive correlation approaching statistical significance, which the authors considered to be spurious. However, the study authors did find a significant correlation with multiple myeloma (bone marrow cancer) which they found to be credible (Study No. 2). A methodological study found significant under reporting of diseases among Hanford workers when death certificates were compared with Social security disability claims (Study No. 4).

Oak Ridge National Laboratory, Tennessee. All cancer mortality was found to have a positive correlation with radiation exposure and indicates that sensitivity to radiation-induced

cancer increases with older ages at exposure (Study No. 5). A second and earlier study found a low overall death rate when compared with the general public, which is consistent with a “healthy worker effect.” However the authors also found an increased risk of dying from all cancers, which is 10 times greater than extrapolations from high dose studies of Japanese A-bomb survivors (Study No. 6). A third study found that adjustment for date of hire, employment duration, or exposure to beryllium, lead and mercury had little effect on radiation risk estimates (Study No. 7).

Oak Ridge Y-12 weapons Plant, Tennessee. Total mortality was low as expected for this group, indicating a healthy worker effect. The study also found elevated death rates for brain cancer, several lymphopoietic (immune system) cancers, as well as cancers of the prostate, kidney and pancreas. Excess death from breast cancer among women was found. The authors found excess lung cancer as their main finding and urged that this disease warrants continued surveillance (Study No. 8). An earlier study found similar risks, with a marginal dose-response trend for lung cancer only (Study No.9).

The K-25 Gaseous Diffusion Plant, Tennessee. Excess risks of dying from all causes were found for white males when compared to general population rates. Other statistically significant increases among white males were for cancers of the respiratory system, bone cancer, mental disorders and all respiratory diseases including pneumonia. Generally the excess deaths from diseases among females were similar to males. Upon further analysis, increased risks of dying from kidney cancer and chronic nephritis (kidney disease) were found. The latter condition was more than 600 percent higher when deaths from the last decade of follow up were observed (Study No. 10).

Fernald Uranium Processing Plant, Ohio. Significant increased risks of dying from stomach cancer were found among salaried workers (261 percent higher than expected). For hourly workers statistically significant increased death risks were found for all cancers (21 percent higher) and lung cancer (26 percent higher). The authors concluded that there is evidence of a radiation-dose relationship for both nonmalignant respiratory diseases and lung cancer (Study No. 11).

Los Alamos National Laboratory, New Mexico. Overall mortality was quite low, indicating a strong “healthy worker” effect due to the high socioeconomic status of laboratory employees. When internal comparisons were used, dose-response relationships from exposure to external radiation and tritium were observed for cancers of the brain, central nervous system, esophagus and Hodgkin’s Disease. When plutonium exposed workers were excluded, significant positive dose response relationships were found for kidney cancer and lymphocytic leukemia (Study No. 13). A case of bone cancer was also found in a worker exposed to plutonium at an exposure level less than half the official lifetime limit (Study No. 12).

Linde Air Products Co., NY. Statistically significant increased risks of dying from all causes (18 percent higher), laryngeal cancer (447 percent higher), all circulatory diseases (18 percent higher), arteriosclerotic heart disease (19 percent higher), all respiratory diseases (52 percent higher) and pneumonia (217 percent higher) were found among workers who processed uranium at this facility between 1943 and 1949 (Study No. 14).

Mallinkrodt Chemical Works, Missouri. Workers who processed uranium between 1942 and 1966 were found to have a significant increased death rate from all cancers (10 percent higher). Respiratory diseases, chronic nephritis/kidney disease (218 percent higher) and lymphatic cancers were significantly elevated. In particular, significant increased risks were found for cancers of the esophagus (40 percent higher), rectum (45 percent higher), pancreas (31 percent higher), larynx (36 percent higher) kidney (34 percent higher) and multiple myeloma/bone marrow (33 percent higher). Kidney cancer showed a significant positive dose-response association with external radiation (Study No. 15).

Mound Laboratory, Ohio. Workers exposed to polonium 210 between 1944 and 1972 showed no excess mortality. Workers hired during World War II showed significant elevated risks of dying from cancers of the lung and rectum. No significant dose-response correlations were found (Study No. 16).

Rocky Flats, Colorado. When compared to US death rates, fewer deaths were found for all causes and all cancers except for excess brain tumors, indicating a “healthy worker” effect. When workers with higher internal exposures to plutonium (> 2 nCi) were compared with workers with lower exposures (< 2 nCi), increased risks from dying from all cancers, including cancers of the immune system (lymphopoietic neoplasms), cancers of the esophagus, stomach, colon and prostate were found. When workers with more than one rem of external radiation were compared with workers with less than one rem, increased risks were found for myeloid leukemia, lymphosarcoma, reticulum cell sarcoma, liver cancers and unspecified brain tumors. No overall dose-response relationships were found for plutonium or external radiation exposures. Internal comparisons indicated that deaths from all causes and all cancers increased as internal plutonium body burdens increased. Risks of dying from cancers of the immune system and brain tumors increased with as external radiation exposures increased (Study No. 17).

The Savannah River Site, South Carolina. A strong “healthy worker” effect was found when worker death rates were compared with the US white males. A significant positive dose-response correlation was found for leukemia and external radiation exposure. The risk increased between 7.81 percent and 18.28 percent per 10 milliSievert [a unit of radiation exposure] of exposure. These estimates of risk per unit of exposure are 2 to 6 times higher than leukemia risks derived from Japanese atomic bomb survivors (Study No. 18).

Rocketdyne/Atomics International, California. Workers had a lower death rate than the US population, except for leukemia, which was higher. Internal comparisons of workers

exposed at different dose levels showed increased risks of dying for workers exposed to more than 200 milliSieverts for cancers of the immune system (lymphopoietic) and lung cancer. There was a positive correlation between increasing doses to external radiation and increased risk of dying from all cancers and “radiosensitive” solid tumors (Study No. 19).

Portsmouth Gaseous Diffusion Plant. Death from all causes was lower than for the US white male population. Excess cancer risks of dying from cancers of the stomach (18 percent higher) and bone (68 percent higher), immune system (37 percent) and Hodgkin’s Disease (38 percent higher) were found. However, this information is based on an interim progress report presentation and these excess cancers did not appear to be statistically significant (Study No. 20).

Livermore National Laboratory. The incidence rate of malignant melanoma was higher for than for the population of the region based on 19 cases diagnosed from 1972-77. In 1984, based on a review of records for persons with and without melanoma, occupational factors were reaffirmed as being associated with melanoma risk. Later, when the incidence rates for LLNL workers were recalculated for the period 1969-80, higher rates were found for some cancers in addition to malignant melanoma. The incidence rates for salivary gland cancer and rectal cancer, among female Laboratory workers, were above the rates for the region. For male laboratory workers, other nervous system tumors, excluding brain tumors, were higher than expected (Study No. 21).

Multiple Combined Facilities

Hanford, Oak Ridge National Laboratory, the Oak Ridge Y-12 Weapons plant, and the Fernald uranium plant. There was evidence of a risk related to cancer dose for each study cohort and evidence that excess cancers considered as “radiogenic” had the same histological manifestations as naturally occurring cancers. Thus, chronic low-level radiation exposure may have more generalized carcinogenic effects. The risks of dying from radiation-induced cancer were appreciably higher than estimates derived from high-dose studies, principally the Japanese atomic bomb survivors. Radiation sensitivity increased among older workers (Study No. 22).

Hanford, Rocky Flats, Oak Ridge National Laboratory, Sellafield (Britain), the Atomic Energy Authority facilities (Britain) and Atomic Energy of Canada Limited facilities. Based on the main analysis, there was little evidence of an association of all cancer mortality with cumulative radiation dose. Increased risks of dying from radiation-induced cancer were found for single cancer types, including leukemia (excluding chronic lymphocytic leukemia). Alternative analyses found positive correlations between increased risks of dying from all cancers (excluding leukemia) and increasing radiation dose. Dose-response effects were comparable to high-dose studies (Study No. 23).

Tennessee Eastman Facility (TEC) at Oak Ridge, the Y-12 weapons facility, the Oak Ridge K-25 Gaseous Diffusion facility, and the Oak Ridge National Laboratory. Deaths from all causes were comparable to the US population, indicating an absence of a “healthy worker effect.” There was a notable excess of lung cancer (12 percent higher). A more detailed analysis revealed substantial differences in death rates among workers at the Oak Ridge Plants. Workers at the Oak Ridge National Laboratory who had more extensive radiation monitoring showed a positive dose response correlation (Study No. 24).

Hanford, Oak Ridge National Laboratory, and Rocky Flats. Little evidence was found of a positive dose-response correlation with exposure to external radiation. Cancers of the larynx and Hodgkin=s disease showed a significant correlation with dose, but the authors gave little credence to these findings. Evidence of an increase in excess risk of dying from cancer with increasing age was found for all cancers at Hanford and Oak Ridge National Laboratory with significant correlations to radiation dose among those 75 years and older (Study No 25).

Fernald, Mallinkrodt, TEC at Oak Ridge and the Oak Ridge Y-12 weapons facility. No positive correlation between radiation dose and dying from lung cancer was found. There is a suggestion of an exposure effect for workers hired after the age of 45 years (Study No. 26).

Rocky Flats, Hanford, Los Alamos, Oak Ridge and the Savannah River Site. This is a study of 260 workers who voluntarily donated their bodies for postmortem analysis for plutonium distribution. Several cancers were found of interest, particularly six brain tumor deaths at Rocky Flats. However, the authors caution that this study is biased by virtue of its small size and the self selection of the population (Study No. 27).

SUMMARY OF DEPARTMENT OF ENERGY (DOE) OCCUPATIONAL RADIATION EPIDEMIOLOGICAL STUDIES

DOE Sites

Hanford

1. Study. Thomas F. Mancuso, Alice M. Stewart and George W. Kneale, *Radiation exposures of Hanford workers dying from cancer and other causes.* Health Physics 1977, 33:369-385.

Worker Population. 35,000 white males who were employed between 1943 and 1972 with 3,520 certifiable deaths.

Radiation Data. The study primarily focused on external penetrating radiation and urine-monitored workers.

Results. *A Data from the Hanford Study have shown that sensitivity to the cancer-induction effects of radiation is at a low ebb between 24 and 45 yr of age. Nevertheless, at younger and older ages there is probably a cancer hazard associated with low-level radiation which probably affects bone marrow cancers more than other neoplasms and cancers of the pancreas and lung.@*

Discussion. The study suggests that according to these estimates, 12.2 rads would be needed to double the normal risk of dying from any form of cancer.

2. Study. Ethyl S. Gilbert, Ellen Omohundro, Jeffery A. Buchanan, and Nancy A. Holter, *Mortality of Workers at the Hanford Site,* Health Physics, June 1993, 64:6:577-590.

Worker Population. 44,154 workers of whom 36,971 were monitored for external penetrating radiation with 6,678 deaths certified as of 1986.

Results. *A Update analyses of mortality of workers at the Hanford site provide little evidence of a positive correlation of cumulative occupational radiation dose and mortality from leukemia and from all cancer except leukemia. Estimates of excess relative risk per 10mSv were negative for both disease categories, but these estimates are consistent both with no risk and with estimates obtained through extrapolation from high-dose data. ...Of 24 specific cancer categories evaluated only cancer of the pancreas and hodgkins disease showed positive correlations with radiation dose that approached statistical significance....These correlations are interpreted as probably spurious. For multiple myeloma, for which a correlation was reported previously, the p value was 0.10. However, a significant correlation ($p < 0.5$) was obtained when analyses were expanded to include deaths with multiple myeloma listed on the death certificates but not*

considered to be the underlying cause, when analyses were expanded to include deaths occurring in Washington State during the time period 1987-1989, or when a 2 y latency period (instead of 10 y) was assumed.@

Discussion. *A Hanford workers continue to show a strong healthy worker effect with death rates from most causes substantially below those of the general U.S. population. ...Dose-response analyses of workers at the UK Atomic Weapons establishment (AWE) and of workers at ORNL [Oak Ridge National Laboratory] show statistically significant correlations for all cancer and risk estimates that are several times those obtained from extrapolation from high-dose data. Data on Hanford workers clearly do not support the high risk estimates obtained from ORNL and AWE data.@*

3. Study. Alice M. Stewart and George W. Kneale, *Relations between age at occupational exposure to ionizing radiation and cancer risk*, Occupational and Environmental Medicine, 1996, 53:225-230.

Worker Population. 35,868 badge monitored workers employed between 1944 and 1989 with 7,874 certified deaths.

Exposure Data. The mean annual dose rate was less than 1 mSv, and there were only 18 times when the maximal permissible dose of 50mSv per annum was exceeded.

Results. *A For radiation received at least 15 years before a cancer death (to allow for cancer latency) evidence of a dose related risk was found which was largely the result of exposures during the last 10 years of working life (between 55 and 65 years of age). The relative frequency of site specific cancers showed no signs being different for radiogenic and idiopathic cancers, and there was no evidence of the exceptionally strong association between radiation and leukemia found in atomic bomb data and other high dose conclusions.@*

Discussion. *A People who are approaching the end of the life span are exceptionally sensitive to all causes of death. Therefore, the idea that old people are less sensitive to carcinogenic effects of radiation than young adults is totally out of line with normal experience...Therefore, although the present findings of a relation between radiation effects and exposure age are at variance with official interpretations of atomic bomb data, this should not be regarded as a reason for doubting that middle aged and elderly workers are far more sensitive to effects of cancer than young recruits. Nor is it unreasonable to suggest that cell killing as well as mutational effects of the atomic bomb radiation contributed to the high death rate from myeloid leukemia in the life span study of the cohort.@*

4. Study. Thomas F. Mancuso, *Methodology in Industrial Health Studies: Social Security Disability Data and the Medical Care System*, American Journal of Industrial Medicine, 1993, 23:653-671.

Worker Population. 35,000 white males who were employed at between 1943 and 1972 with 1,734 disability claims filed with the Social Security Administration.

Exposure Data: The study did not focus on exposures.

Results. *A Comparisons were made of all causes of disability with all causes of death for white males and white females. A remarkably high percentage of causes of disability were not recorded or available by death certificate for ICD categories of diseases and specific cancer sites...The death certificate provides a gross underestimate of the biological effects which may have occurred in that population.@*

Discussion. *A The search for the biological effects among worker cohorts has been mostly in terms of mortality experience. Yet it is well known that the primary and secondary causes of death on a death certificate do not reflect the diseases or illnesses which may have occurred prior to death...The consequences have been the underestimation of the true nature and magnitude of occupational health effects when based solely on death certificates. The Social Security disability data constitute the equivalent national uniform resource on morbidity which can meet this need to a significant extent and provide the means for the simultaneous cohort study of mortality and disability from the same source, the Social Security System.@*

Oak Ridge, TN

5. Study: David Richardson and Steve Wing, Radiation and Mortality of Workers at Oak Ridge National Laboratory: Positive Associations for Doses Received at Older Ages, Environmental Health Perspectives, August, 1999. 107: 8 (Mortality study)

Worker Population: 14,095 workers hired at Oak Ridge National Laboratory (X-10) between 1943 and 1972. The cohort included men, women, white and non-white workers. Deaths were collected up to 1990 with 3,269 workers deceased and 6 percent lost to follow up.

Exposure Data: External penetrating radiation measured by film badges. By 1948, over 98% of the employed workers were monitored and by November 1951 all ORNL workers were required to wear individual dosimeters.

Results: *A Positive associations were observed between low-level exposure to external ionizing radiation and mortality. These associations were larger for doses received after 45 years of age, larger under long lag [latency] assumptions, and primarily due to cancer causes of death. All cancer mortality was estimated to increase 4.98% ... per 10-mSv cumulative dose received after age 45 under a 10-year lag, and 7.3% ... per 10-mSv cumulative dose received after age 45 under a 20 year lag. Associations between radiation dose and lung cancer were of similar magnitude to associations with radiation dose and all cancers except lung cancer. Nonmalignant respiratory disease exhibited a positive association with cumulative radiation dose received after age 45, whereas ischemic heart disease exhibited no association with radiation dose. These findings suggest increases in cancer mortality associated with low-level external exposure to ionizing radiation and potentially greater sensitivity to the carcinogenic effects of ionizing radiation and with older ages at exposure.@*

Discussion. The conclusion that sensitivity to external radiation increases with age among adults is at odds with the Japanese Atomic Bomb Survivors study. Two previous studies of exposed workers showed no evidence of radiation age-sensitivity, whereas, four others have reported dose response associations with older ages of exposure.

Richardson and Wing published a similar set of findings in the International Journal of Epidemiology 1999;28:428-436.

6. Study: Steve Wing, Cary M. Shy, Joy Wood, Susanne Wolf, Donna Cragle, and E.L. Frome, *Mortality Among Workers at Oak Ridge National Laboratory, Evidence of Radiation Effects in Follow-up Through 1984*, Journal of the American Medical Association, March 20, 1991, 265: 1397-1402. (Mortality study)

Worker Population: 17, 517 workers hired between 1943 and 1972 at Oak Ridge National Laboratory. Women and non whites were excluded from the study 8.2 % lost to follow-up. The cohort analyzed was of 8,318 white males with 1,524 people deceased.
Exposure Data. External penetrating radiation measured by film badges. By 1948, over 98% of the employed workers were monitored and by November 1951 all ORNL workers were required to wear individual dosimeters.

Results. *A Relatively low mortality compared with that in the US white men was observed for most causes of death, but leukemia mortality was elevated in the total cohort (68% higher, 28 deaths) in workers who had at some time been monitored for internal radionuclide contamination (123% higher, 16 deaths). Median cumulative dose of external penetrating radiation was 1.4 mSv; 638 workers had cumulative doses above 50mSv (5 Rem). After accounting for age, birth cohort, a measure of socioeconomic status, and active worker status, external radiation with a 20-year exposure lag was related to all causes of death (2.68% increase per 10 mSv) primarily due to an association with cancer mortality (4.94% per 10 mSv.)The radiation-cancer dose response [for all cancers] is 10 times higher than estimates from follow-up of survivors of the bombings of Hiroshima and Nagasaki, Japan, but similar to one previous occupational study.....@*

Discussion: The ORNL cohort has a lower than average overall death rate than the general population and exhibits a Ahealthy worker effect.@ The health worker effect is expected in the group because it is as largely professional, relatively well paid workforce, with access to medical and other social benefits. This study confirms an earlier finding by Mancuso, Stewart and Kneale (Radiation exposures of Hanford workers dying from cancer and other causes, Health Physics , 33;369-385 , 1977) who reported that workers at DOE=s Hanford nuclear site were dying from radiation-induced cancers at exposure levels 10 times lower than current protection standards assume. The ORNL and Hanford studies are at variance with the extrapolated dose-response estimates derived from the Japanese Atomic Bomb Survivor Study.

7. Study. Steve Wing, Carl M. Shy, Joy L. Wood, Susanne Wolf, Donna Cragle, William Tankersley, and E.L. Frome, *Job Factors, Radiation and Cancer Mortality at Oak Ridge National Laboratory: Follow-up through 1984*, American Journal of Industrial Medicine, 1993, 23:265-279.

Worker Population. 8,318 workers hired at the Oak Ridge National Laboratory between 1943 and 1972, with 1,524 known to have died and 686 were lost to follow up.

Exposure Data. External radiation was measured by personal dosimeters for 95% of work-years, and the remaining doses were estimated from a worker=s data within 2 years of the missing year or from other workers= records. Internal doses were not considered to be a major problem at this facility and were not considered.

Results. *AA previous study of mortality among white men hired at Oak Ridge National Laboratory between 1943 and 1972 revealed an association between low-dose external penetrating ionizing radiation and cancer mortality in follow-up through 1984. The association was not observed in follow-up through 1977. This report considers the role of possible selection and confounding factors not previously studied. Control for hire during the World War II era and employment duration of less than 1 year had little effect on radiation risk estimates....Adjustment for potential exposures to beryllium, lead and mercury also had little effect on radiation risk estimates. These analyses suggest that selection factors and potential for chemical exposure do not account for the previously noted association of external dose with cancer mortality. However, power to detect effects of chemical exposures is limited by a lack of individual exposure measures.*

Discussion. The earlier 1984 report by Wing et al. was met with considerable skepticism due to the finding of an unexpectedly large relationship between low-level external penetrating ionizing radiation and deaths from cancer. However, the expectation that dose-response estimates from various studies should converge around some Atrue@ value that represents a Alaw@ of radiation dose-response is naive. Radiation effects may be expected to vary with population differences in health status, susceptibility, and selection factors, all of which may be influenced by many other factors.

8. Study. Dana P. Loomis and Susanne H. Wolfe, *Mortality of Workers at a Nuclear Materials Production Plant at Oak Ridge, Tennessee, 1947-1990*, American Journal of Medicine, 1996, 29:131-141.

Worker Population. 8,116 men and women employed at the Oak Ridge Y-12 uranium processing facilities between 1947 and 1974 with 1,861 deaths as of 1990 and 206 lost to follow up.

Exposure Data. Workers handled various compounds of uranium 235 and uranium 238 and were exposed to both external penetrating radiations and internal depositions. Other agents used at Y-12 include solvents, machine oils, mercury, lead and beryllium. Prior to 1960 the majority of Y-12 workers were not monitored for external radiation.

Results. *ATotal mortality was low for all Y-12 workers and total cancer mortality was as expected ...Death rates from brain cancer and several lymphopoetic system cancers were also elevated among white men with SMRs of 1.28 and 1.46. Mortality from cancer of the pancreas, prostate, and kidney was similarly elevated. There was evidence of excess breast cancer among the 1,073 female workers (SMR 1.21 95% CI...). Lung cancer mortality among these workers warrants continued surveillance because of the link between internal alpha radiation exposure and this disease, but other agents, notably beryllium, also merit consideration as potential causes of lung cancer. Other cancers and*

agents should also be investigated as part of a comprehensive study of the health consequences if the production of nuclear weapons.@

Discussion. This is a multiple cohort study which looked at males, females, and people of color. By virtue of their numbers, white males exhibited less favorable mortality experiences. These findings are consistent with an earlier study of this population based on follow-up through 1979.

9. Study. Harvey Checkoway, Neil Pierce, Douglas J. Crawford-Brown, and Donna Cragle, *Radiation Doses and Cause-Specific Mortality Among Workers at a Nuclear Materials Fabrication Plant*, American Journal of Epidemiology, 1998, 127:2:255-266.

Worker Population. 6,781 white males employed at the Oak Ridge Y-12 weapons facility from 1947 to 1974 with 862 deaths identified with 846 death certificates obtained through 1979.

Exposure Data. Workers handled various compounds of uranium 235 and uranium 238 and were exposed to external penetrating radiations and internal depositions. Other agents used at Y-12 include solvents, machine oils, mercury, lead and beryllium. Prior to 1960 the majority of Y-12 workers were not monitored for external radiation. Among monitored workers, the mean cumulative dose to the lung was 8.21 rem, and the mean cumulative external whole body penetrating dose from gamma radiation was 0.96 rem.

Results. *Relative to the U.S. white males, the cohort experienced mortality deficits from all causes combined, cardiovascular diseases, and for most site specific cancers. Mortality excesses of lung and brain and central nervous system cancers were seen from comparisons with national and state rates Dose-response trends were detected for lung cancer mortality with respect to cumulative alpha and gamma radiation, with the most pronounced trend occurring for gamma radiation among workers who received > one rem alpha radiation. ...While these rate ratios, which are based on three and one death, respectively, lack statistical precision, the observed dose-response trends indicate potential carcinogenic effects to the lung of relatively low-dose radiation. There are no dose-response trends for mortality from brain and central nervous system cancers.@*

Discussion. *The finding of a dose-response relation with cumulative gamma radiation dose among workers who received the highest doses of alpha radiation points out the importance of continued follow-up of this and other populations exposed to low doses. A rate ratio among workers who received > 5 rem of radiation from both internal and external sources of 4.60 and 3.05... far exceeds the rate ratio 1.01 that would be predicted by the National Council on Radiation Protection and Measurement estimate of 1.4 excess cancers per million person-rem.@*

10. Study. Elizabeth A. Dupree, Susan M. Wells, Janice P. Watkins, Phillip W. Wallace, Nancy C. Davis, *Mortality Among Workers Employed between 1945 and 1984 at a Uranium Gaseous Diffusion Facility*, Draft Report, Oak Ridge Institute for Science and Education. (no date)

Worker Population. 37,712 workers of both genders and all races employed at the Oak Ridge K-25, Gaseous Diffusion Plant from 1945 to 1984. Death certificates were

collected up to 1985 with 95% available for those known to be deceased. There were 10,457 individuals or 29.8% of the total cohort who were lost to follow-up and no longer contributed person-years as of January 1, 1979.

Exposure Data. Workers were exposed to external penetrating radiations from uranium isotopes and internal alpha and other radiations deposited in the body. (The presence of fission products from recycled uranium was not considered in this study). The vast majority of the K-25 workers were not badged until 1975. Other agents to which workers were exposed include, epoxy resins and hardeners, metallic nickel, uranium hexafluoride (UF-6), insoluble uranium oxides, hydrofluoric acid, solvents and a variety of chemicals, especially fluorocarbons.

Results. *For white males the SMR [Standardized Mortality Ratios B ie. comparisons with members of the public] for all causes of death, 1.03 [95% confidence Interval...] was statistically significantly increased. For nonwhite males the SMR approached unity (SMR=0.95). Other statistically significant increases among the white males were for cancers of the respiratory system (SMR=1.17) including lung cancer (SMR=1.19); bone cancer (SMR=1.82); mental disorders (SMR=1.59) all respiratory diseases (SMR= 1.19) including pneumonia (SMR=1.17); symptoms, senility and ill defined conditions (SMR=3.01)....Among the non-white males no cause of death showed a statistically significant increase; however, there was an excess of deaths from cancer of the respiratory system (SMR=1.36) including lung cancer (SMR=1.36.... Regardless of race, the SMR for females for all causes of death was about unity. Statistically significant increases among females occurred only for symptoms, senility and ill-defined conditions (white SMR= 2.27; no-white SMR= 2.49). Generally, the SMRs that were elevated for males were also elevated for females.... In summary, the outcomes of interest a priori in this study were elevated in many instances. In general, the excess risk was in hourly workers, workers employed less than a year and workers born before 1910. These categories were also the ones that occurred most frequently in the cohort....For kidney cancer and chronic nephritis, an elevated SMR was found upon stratifying the white males. However, for chronic nephritis a statistically significant SMR of 6.41 was observed in the last decade of follow up.@*

Discussion. Unlike most worker studies, no health worker effect was seen for K-25 workers. Although processing operations at K-25 continued long after WWII, there was evidence of the lack of a healthy worker effect in the K-25 cohort which may have resulted from workers employed during WWII. Also in workers employed less than a year excess mortality was observed, raising a question of how a short period of employment could have an adverse effect on health. Other factors such as smoking, which were not measured in this study could account for some of the excess risk. However, because many of the sites of a priori interest showed an excess risk makes it difficult to dismiss the results despite the short period of employment.

Fernald, OH

11. Study: Donna L. Cragle, Janice P. Watkins, J. Nicholas Ingle, Kathryn Robertson-Demers, William G.. Tankersley, Charles M. West, *Mortality Among a Cohort of White Male Workers at*

a Uranium Processing Plant: Fernald Feed Materials Production Center [FMPC], Radiation Research (not sure if it is published)

Worker Population: A cohort of 4,014 white males hired at the FMPC between 1951 and 1981 with 1,064 deceased workers. Less than one percent were lost to follow-up.

Exposure Data. Weekly external radiation monitoring began at Fernald in 1952 for employees having the highest exposure potential. Employees with lower exposure potential were monitored bi-weekly. By the mid-1950's, all workers were monitored monthly. Internal exposure monitoring first began in 1952 with workers monitored on a non-routine basis until 1958 when quarterly urinalysis sample collection for process workers and semiannual collections for other workers became a primary means of internal exposure monitoring. In 1968 in vivo radiation monitoring was done biannually. Much of the lung exposure was due to insoluble uranium compounds. The Fernald workers were also exposed to multiple chemicals such as nitric acid, sodium hydroxide, tributyl phosphate, trichlorethelene and kerosene. [Inadequate and infrequent personnel exposure monitoring combined with an extensive documented history of wide-spread contamination throughout the facility, makes individual exposure data tenuous at best.]

Results: *ASMR=s stratified by paycode showed a healthy worker effect in salaried, but not hourly employees when compared to mortality rates of U.S. white males. Significant increases were noted for salaried workers for deaths from stomach cancer (SMR= 2.61, 90% confidence interval)... and for hourly workers for all cancer (SMR = 1.21)..., [and] lung cancer (SMR =1.26)...Trend test statistics revealed a borderline significant trend for lung cancer ...with external dose. Trend tests for non-malignant respiratory diseases were significant for chronic respiratory diseases with internal dose. Dose-response analyses for lung cancer with external dose revealed an excess relative risk per Sv of 8.0 (90% C.I....) with a 10 year lag [latency] and 10.7 with a 15 year lag. Models of lung cancer with internal dose revealed no significant relationship. Dose-response analyses for non-malignant respiratory diseases and internal dose resulted in an excess relative risk per GY of 13.8... with a 10 year lag and 14.2 with a 15 year lag.... We conclude that there is evidence of a radiation dose-response relationship in this population for both non-malignant respiratory diseases and lung cancer.@*

Discussion. The absence of a healthy worker effect among hourly workers was unusual, particularly since deaths from diseases of the circulatory system in both hourly and salaried workers reflected evidence of a healthy worker effect. The significant increase in deaths among hourly workers from cancers is the result of generalized increases in deaths in 14 of 17 cancer categories. Excess lung cancer is generally not recognized as a consequence of external radiation exposure. Another study of DOE uranium fabrication workers at the Oak Ridge Y-12 facility, found a similar relationship.

Los Alamos

12. Study. George L. Voelz and J.N.P. Lawrence, *A 42-Year Medical Follow-up of Manhattan Project Plutonium Workers*, Health Physics, August 1991, 61:2:81-191.

Worker Population. 26 white males who worked with plutonium during World War II at Los Alamos. These workers had medical examinations about every 5 years since 1952.

Exposure data: Inhalation was the primary means of exposure. Plutonium doses were estimated based on urine excretion data and seven men received whole body counts. These workers are estimated to have a range of plutonium depositions from 5% to 200% of the lifetime occupational protection guideline with ten persons having plutonium burdens at or above the lifetime limit.

Results. *A Four persons from the original group have died as of 1987. Expected deaths based on U.S. death rates of white males, adjusted for age and calendar year, are 9.2 based on U.S. rates (SMR=0.41). Subsequent to 1987, three additional deaths occurred from atherosclerotic heart disease, lung cancer and osteogenic sarcoma.... To our knowledge, this case is the first person exposed to plutonium in which a bone sarcoma has been reported....Osteogenic sarcoma is also the predominant bone tumor resulting in dogs from plutonium-239 injections....The incidence of bone cancer in man is ordinarily low. In a group of 26 adult males over a 40+ year period the likelihood of observing such a case is only about 1%...The estimated Plutonium deposition in this man at the time of death is 560Bq (15nCi).@ [more than twice the lifetime limit of 40 nCi]*

Discussion. This study shows a pronounced unhealthy worker [effect@](#), but the small number of people in the study makes it difficult to assign statistical significance. Of significance is the case of osteosarcoma because members in this group have a 1 in 100 chance of dying from this disease.

13. Study. Laurie D. Wiggs, Emily R. Johnson, Carol A. Cox-DeVore, and George L. Voelz, Mortality through 1990 Among White Male Workers at the Los Alamos National Laboratory: Considering Exposures to Plutonium and External Ionizing Radiation, Health Physics, December 1994, 67:6:557-586.

Worker Population. A cohort of 15,727 white men employed at Los Alamos National Laboratory from 1943 to 1977. There were 1,349 deaths identified with less than one percent lost to follow-up.

Exposure Data: Workers were monitored for external radiation since 1944. Workers were also monitored for internal exposures to plutonium tritium and other isotopes through urinalysis and *in vivo* methods, beginning in 1944. [No mention is made of possible neutron exposures.]

Results. *The results indicated that overall mortality among this cohort is quite low...No cause of death significantly elevated among plutonium-exposed workers, when compared to unexposed coworkers; however a rate ratio for lung cancer of 1.78 (95% C.I....) was observed. A case of osteosarcoma, a type of cancer related to plutonium exposure in animal studies was also observed. Dose response relationships for whole-body dose from external ionizing radiation and tritium were observed for cancers of the brain/central nervous system, the esophagus, and Hodgkin=s disease.... We conducted additional analyses to determine whether the dose-response analyses for external radiation were confounded by the dose from plutonium. When plutonium exposed workers were excluded.....The significant dose response trends for Hodgkin=s disease, malignant*

neoplasms of the brain/CNS and cancers of the esophagus remained significant with the trend test statistic increasing by an order of magnitude in all instances. The dose-response trend became statistically significant for cancers of the kidney (12, $p = 0.02$, 10yr lag) and lymphocytic leukemias ($p = 0.04$, 2-y lag).@

Discussion. The Los Alamos workforce shows a pronounced healthy worker effect with a 35 percent deficit in deaths from all causes. Recognizing this, the authors utilized additional methods to compensate for the healthy worker effect to determine if there were relative increased risks and dose-response trends associated with plutonium and exposure to external penetrating radiations and tritium.

Linde Air Products Company, Tonowanda, NY

14. Study. Elizabeth A. DuPree, Donna Cragle, Richard, W. McLain, Douglas Crawford-Brown, M. Jane Teta, *Mortality among workers at a uranium processing facility, the Linde Air Products Company Ceramics Plant, 1943-49*, Scandinavian Journal of Worker and Environmental Health, 1987, 13:100-107.

Worker Population. 995 white men who were employed at the Linde Ceramics Plant employed more than 30 days between 1943 and 1949. Mortality data was collected for 429 men up to 1979 with 5.7% lost to follow up.

Exposure Data. Workers exposed to uranium (ore with a high radium-226 content, uranium oxide, uranium trioxide and uranium dioxide) and tetrafluoride were studied. Other non-radioactive exposures included nickel powder, chlorine, hydrofluoric acid, lead sulfate, nitric acid, nitrogen oxides, silicon dioxide, and sulfuric acid.

Results. A...*Statistically significant increased standardized mortality ratio (SMR) values were observed for all causes (SMR 118) Laryngeal cancer (SMR 447), all circulatory diseases (SMR 118), arteriosclerotic heart disease (SMR 119), all respiratory diseases (SMR 152) and pneumonia (SMR 217). Site specific outcomes of special interest with a statistically increased number above expected were laryngeal cancer (observed 5) and pneumonia (observed 17). No association was found with length of employment or work in the most hazardous areas of the plant.@*

Discussion. It is unusual to find an elevated all-cause death rate above that of the general public in an occupational group. The lack of excess lung cancer mortality is contrary to what has been seen on studies of other uranium workers, particularly uranium miners.

Mallinckrodt Chemical Works, St. Louis, MO.

15. Study. E. DuPree Ellis, J.P. Watkins, J.N. Ingle, J.A. Phillips, *External Radiation Exposure and Mortality Among a Cohort of Uranium Processing Workers*, Oak Ridge Associated Universities, Oak Ridge TN, (unpublished report).

Worker Population. 2, 514 white men employed in a uranium processing plant between 1942 and 1966 with 1056 deaths ascertained through 1993 and 45 workers lost to follow up.

Exposure Data. The primary exposure concern of this study is to external radiation. During the early period of operation this facility processed uranium ore with a high radium-226 content which led to increased external gamma and beta radiation exposures. The study does not reference other exposures found at similar uranium foundries such as the Fernald facility in Ohio. Beginning in 1945, workers were monitored for external radiations.

Results. *Standardized Mortality Ratios (SMRs) were calculated for 56 causes of death. Annual external radiation doses were obtained from individual film badge readings. ...SMR with a 95% CI [confidence interval] was 0.92...for all causes and 1.10 for all cancers; respiratory diseases, chronic nephritis, and lymphatic cancers were significantly elevated..... Among the organ systems of particular interest, cancer sites with at least a 30 percent excess over expected were esophagus (SMR=1.40, 95% CI), rectum (SMR =1.45, 95% CI), pancreas (SMR 1.31, 95% CI), larynx (SMR 1.36, 95% CI), kidney (SMR 1.34, 95% CI), and multiple myeloma (SMR= 1.33, 95% CI). Among the nonmalignant outcomes of interest, only chronic nephritis (SMR=2.18, 95% CI)...exhibited such an excess. Trend tests revealed a statistically significant increase in kidney cancers based on 11 deaths (p=0.02) with a relative risk estimate per Sv of 12.9 with 90% CI. The only disease of a priori interest with evidence of exposure related effect was kidney cancer. While this appears to be related to exposure to radium and its daughters resulting from high grade uranium ore processing prior to removal of the radium component, it must be considered provisional since external radiation exposure may be a surrogate for internal radiation dose or chemical exposures which were not considered in this study.*@

Discussion. A relationship between kidney cancer and external radiation exposure has been reported in three nuclear worker studies done in Great Britain.. There are a number of weaknesses in this study. These include the small size of the cohort, workers lost to followup assumed to be alive, and the failure to consider internal radiation and chemical exposures. Personal external radiation monitoring data was missing for 20.8 percent of the total 16,573 employment years of the cohort.

Mound Laboratory, Miamisburg, OH

16. Study. Laurie D. Wiggs, Carol A. Cox-DeVore and George Voelz, *Mortality Among a Cohort of Workers Monitored for Polonium-210 Exposure: 1944-1972*, Health Physics, July 1991, 61:1:71-76.

Worker Population. 4,402 white men employed at the Mound facility from 1944 to 1972 with 961 persons identified as deceased with 26 workers lost to follow up.

Exposure Data. The study focused entirely upon exposure to polonium-210 (Po-210) a naturally-occurring decay product of uranium. 2181 white males were monitored for Po-210 uptake.

Results. *A ...during the period when Po-210 operations were conducted (1944-1972), no excess mortality was observed. Among workers hired during World War II mortality was elevated, especially for deaths from all cancers, cancers of the lung, and cancers of the*

rectum. These adverse health effects do not appear to be related to exposure to Po-210. Among workers monitored for Po-210, mortality was significantly less than expected, although more lung cancers were observed than expected. No significant dose-response trends were identified for all causes combined, all cancers combined, or for cause-specific cancers among the Po-210-monitored subcohort.

Discussion. Mound workers were exposed to multiple radionuclides such as PU-238 and H-3 which were not included in this study. The excess cancer death rates for workers hired during World War II is not reflected among workers hired after 1945. While there may be several explanations for the excess cancers among people hired during World War II, such as not being healthy enough to serve in the military, or smoking habits, it is impossible to know whether these factors existed.

Rocky Flats, CO

17. Study. Wilkinson, G.S., G.L. Teitjen, L.D. Wiggs, W.A. Gaike, J.F. Aquavella, M. Reyes, G.L. Voelz and R.J. Waxweiler, *Mortality Among Plutonium and other Radiation Workers at a Plutonium Weapons Facility*, American Journal of Epidemiology, 1987, 125:2.

Worker Population. 5,413 white males employed at the Rocky Flats plutonium foundry for at least two years between 1952 and 1979 with 409 deaths observed.

Exposure Data: The study focused on ionizing radiations including gamma photons, beta, and alpha particles, and neutrons. Exposure data was drawn from annual external radiation exposure summaries, and bioassay data for internal plutonium depositions.

Results. *When compared with US death rates, fewer deaths than expected were found for all causes of death, all cancers, and lung cancer. No bone cancer was observed. An excess of brain tumors was found in the cohort in general. Elevated rate ratios for all causes of death and all lymphopietic neoplasms were found when employees with plutonium body burdens >2 nCi were compared with those with body burdens < 2 nCi, while accounting for age, calendar period, and induction time. Increased rate ratios were also found for esophageal, stomach, colon and prostate cancer, and for lymphosarcomas and reticulum cell sarcomas. No elevated rate ratios were noted for bone or liver cancers. When employees with cumulative exposures >1 rem were compared with those exposures < 1 rem, elevated rate ratios were found for myeloid leukemia, lymphosarcoma and reticulum cell sarcoma, liver neoplasms, and unspecified brain tumors. No overall dose-response relationships were found for plutonium or external radiation exposures. Standardized rate ratios increased, however, as plutonium body burden levels increased for all causes, all cancers, and digestive cancers at five years induction time. Standardized rate ratios also increased as external radiation exposure categories increased for all lymphopietic cancers and unspecified brain tumors for a two year induction period..A*

Discussion. *A With the exception of analysis of combined categories of death, and perhaps lung cancer, confidence limits were wide, indicating limited precision. Nevertheless, these findings suggest that increased risks for several types of cancer cannot be ruled out at this time for individuals with plutonium body burdens of > nCi. This study is first to report an association between plutonium exposure and adverse*

health outcomes. Cancers of the brain, lymphatic organs, lung, and blood forming organs are consistent with published findings of other exposed groups. Cancers of the Digestive system and prostate require further examination. In addition, plutonium workers may be exposed to potentially hazardous chemicals. Still to be resolved are the lack of dose-response for many of the elevated rate ratios. A

The Savannah River Site, SC

18. Study. Donna Cragle, Kathryn Robertson-Demeyers, and Janice P. Watkins, Mortality Among Workers at a Nuclear Fuels Production Facility: The Savannah River Site, 1952-1986, Oak Ridge Institute for Science and Education, (submitted manuscript).

Worker Population. 9,860 white male workers employed for more than 90 days between 1952 and 1974 with 1,722 deaths through 1986.

Exposure Data: During 1952-1957 film badges were processed on a weekly basis, and processed bi-weekly from 1958-1964. In 1965 badges were processed on a monthly basis which is the current practice. Exposures included external penetrating radiations, including neutrons, which were measured after 1971, and internal exposures to beta, gamma and alpha emitters, most notably tritium and plutonium. Bioassay data included urinalysis and whole body counts. External radiation dose equivalents were available for 9,757 of the 9,860 workers in the cohort. Data on fission products and/or transuranics are available for 408 of the 455 workers evaluated for internally deposited radionuclides.

Results. *A strong healthy worker effect was noted when the population compared with mortality rates in U.S. White males. Radiation dosimetry data for...99% of the cohort. Cumulative population dose was 399 Sieverts (Sv) with a mean and median dose per worker of 40.9 milliSieverts (Msv) and 76. mSv respectively. Dose-response analysis were performed for all cancers, lung cancer, leukemia, colon cancer, and pancreatic cancer. Only the analysis for leukemia revealed a positive and significant dose-response with the increase in mortality per 10 Msv estimated to be 7.81 percent with a two year lag using a multiplicative relative risk model (MRR) and 18.28 percent using an excess relative risk model ERR).@*

Discussion. Because the Savannah River Site, was managed by one contractor, the DuPont Corporation, from 1952 to 1987, it is considered to have perhaps the best dosimetric data on its employees in the DOE complex. This is the fourth and most recent occupational study of nuclear workers that shows a positive dose-response relationship for leukemia. The other three are of nuclear workers in Great Britain.^{2 3 4}

² Kendall GM, Muirhead CR, MacGibbon BH et al. *Mortality and occupational exposure to radiation: first analysis of the National registry for Radiation Workers*, British Medical Journal, 1992, 304:220-25.

³ Smith PG, Douglas AJ. *Mortality of workers at the Sellafield Plant of British Nuclear Fuels*. British Medical Journal, 1986, 845-54.

⁴ Carpenter L, Higgins C., Douglas A. et al. *Combined analysis mortality in three United Kingdom nuclear industry work forces, 1946-1988*, Radiation research, 1004:138:224-38.

Rocketdyne/Atomics International, CA

19. Study. Beate Ritz, Hal Morgenstern, John Froines, and Bambi Batts, Effects to External Ionizing Radiation on Cancer Mortality in Nuclear Workers Monitored for Radiation at Rocketdyne/Atomics International, American Journal of Industrial Medicine, 1999, 35:21-31.

Worker Population. 4,563 workers employed by Rocketdyne/Atomics International who were enrolled in the company's health physics radiation monitoring program between 1950 and 1993. Mortality on 875 individuals were obtained up to 1995, with one lost to follow up.

Exposure Data. Most external-radiation monitoring involved whole-body doses of gamma rays and x-rays. Records also contain readings of exposure to beta radiation and neutrons. More than 90% of the internal exposure records reported urinalysis measurements of either uranium or mixed- fission products.

Results. *Of the 875 deaths that occurred before 1995, 258 were due to cancer as an underlying cause. External comparisons of male subjects with the U.S. white male population indicated that workers had lower rates of dying from all causes and all cancers, but a higher rate of dying from leukemia. Internal comparisons of workers exposed at different dose levels using risk-set analyses with adjustments for cofounders, demonstrated an increased mortality rate in workers exposed to 200 mSv for hemato- and lymphopietic cancers and for lung cancer. Mortality rates for total cancers and Aradiosensitive@ solid cancers increased monotonically with cumulative radiation dose, but no trends were observed for Anon radiosensitive@ cancers.*

Discussion. AConclusions *Despite possible residual confounding and low precision for estimating effects on specific cancers these findings indicate that chronic low-level radiation exposure may have more generalized carcinogenic effects than have been observed in most previous investigations. Such effects may have become evident as a result of the relatively long follow-up period in the present study.@*

The Portsmouth Gaseous Diffusion Plant

20. Study. Steven H. Ahrenholz, John J. Cardelli, Patricia A. Dill, Richard Hurnung, Dianne Reeder, Thrumann Wenzl, *A Mortality Study of Workers at the Portsmouth Gaseous Diffusion Plant*, Summary Progress Report, National Institute for Occupational Safety and Health, no date, (study not completed).

Worker Population. 8,887 workers (both genders, all races) with 53,304 job assignments employed for at least one day between 1954 and 1991.

Exposure Data: Substances to which workers were exposed include internal exposure to uranium hexafluoride, uranium, fluorine, and nickel. (Recently, further awareness about the presence of fission and transuranic products from the recycling of previously irradiated uranium has emerged)

Results. In 1987 a report done for NIOSH by Brown and Bloom found a deficit in all causes of death (SMR=68) and all cancers (SMR=85), which are consistent with a healthy worker effect. They also found an excess of stomach cancer (SMR=1.69) and hematopoietic cancers (SMR= 1.46). It is not known based on this document if these

excess death rates were statistically significant. In 1992, an updated analysis was initiated which found an all cause death rate (SMR of 0.72; CI=0.67-0.76). There were 313 deaths from cancer with an SMR for all cancers of 0.82; CI=0.73-0.92. Elevated risks were found with respect to cancers of the stomach (15 cases, SMR= 1.18; CI=0.65-1.94) and bone (2 cases, SMR=1.68; CI=0.20-6.05). Excess deaths from lympho-reticulosarcoma (7 cases, SMR=1.37; CI=0.55-2.82) and Hodgkins disease (5 cases, SMR 1.38; CI=0.45-3.23) were found.

An analysis of deaths of workers with internal alpha exposures found an SMR of 0.73; (CI=0.68-0.78). A trend analysis comparing SMR=s for all causes, stomach cancer, lung cancer and lympho-hematopoietic cancers with increased internal exposures were of limited precision due to small numbers.

Discussion. According to the document prepared by NIOSH the study has several limitations including:

A young cohort

A mortality study versus a morbidity study.

Life-table analysis, does not address confounding and effect modification.

Exposure metrics leave much to be desired.

The study cannot be readily generalized to other radiation exposed cohorts.

21. Study. DF, Reynolds PJ. Investigation of an excess of melanoma among employees of the Lawrence Livermore National Laboratory. *American Journal of Epidemiology* 1997; 145:524-531.

Worker Population. 5,100 LLNL employees at the Livermore National Laboratory.

Exposure Data: External Penetrating Radiation and internal exposures.

Results. *A This population has been subject to several studies.⁵ The incidence rate of malignant melanoma was higher than for the population of the region based on 19 cases diagnosed from 1972-77. Work involving exposure to ionizing radiation was not associated with a diagnosis of melanoma; working as a chemist was. In 1984, based on a review of records for persons with and without melanoma, occupational factors were reaffirmed as being associated with melanoma risk. Later, when the incidence rates for LLNL workers were recalculated for the period 1969-80, higher rates were found for some cancers in addition to malignant melanoma. The incidence rates for salivary gland cancer and rectal cancer, among female Laboratory workers, were above the rates for the region. For male*

⁵ Austin DF, Snyder MA, Reynolds PJ, Biggs MW, Stubbs HA. Malignant melanoma among employees of Lawrence Livermore National Laboratory. *Lancet* 1981; 2:712-716. Reynolds P, Austin DF. *Cancer incidence among employees of the Lawrence Livermore National Laboratory, 1969-1980.* *Western Journal of Medicine* 1985, 142:214-218. Shy CM, Checkoway H, Marshall EG. Malignant melanoma at a scientific laboratory. *A synthesis of reviewer=s comments on the Austin and Reynolds study of employees at the Lawrence Livermore National Laboratory.* Lawrence Livermore National Laboratory Report No.: UCRL-15737 (S/C 7532605) 15 Nov 1985, 57 pp. Contract Number W-7405-ENG-48. Schwartzbaum JA, Setzer RW, Kupper LL. *An exploratory analysis of the occupational correlates of large pigmented nevi at Lawrence Livermore National Laboratory.* *Journal of Occupational Medicine* 1990; 32:605-611. Austin DF, Reynolds PJ. *Occupation and malignant melanoma of the skin.* In: *Recent Results in Cancer Research* 1986, 102:98-107. Berlin:Springer-Verlag.

laboratory workers, other nervous system tumors, excluding brain tumors, were higher than expected. Thirty one laboratory workers with malignant melanoma and a control group were interviewed about personal and occupational factors that might be associated with the disease. Five factors were more common than expected among persons with malignant melanoma. These were judged to contribute independently to a persons risk of melanoma. They were exposure to radioactive materials, work at Site 300, exposure to volatile photographic chemicals, participant at the Pacific Test Site, and chemist duties. The most recent interview study of 69 cases and an equal number of controls found that differences in personal factors, genetics, and recreational use of the outdoors were consistent with what is known about malignant melanoma of the skin. Only occupational exposure to alcohols, out of 39 industrial exposures examined, was more common among persons with melanoma. Several special studies of the microscopic features of the melanoma tumors indicated that the tumor thickness among laboratory workers was significantly less than for individuals that did not work at LLNL, at least up to the time when the concern became public in 1977. These data on microscopic features were taken as evidence of medical over diagnosis of tumors. at LLNL. A greater proportion of workers hired before 1962, who were engineers, particularly electrical engineers, had dark moles or pigmented nevi that are associated with a high risk of malignant melanoma.@⁶

Discussion. The numerous studies about this situation reflect an extraordinary amount of attention being paid by the Livermore National Laboratory and the DOE to this issue. Unlike most other DOE studies of industrial populations, the level resources spent to debate whether or not excess cancers are job-related at LLNL is quite high.

Multiple Combined Facilities

22. Study. George W. Kneale and Alice M. Stewart, *Factors affecting recognition of cancer risks of nuclear workers*, Occupational and Environmental Medicine, 1995, 52:515-523.

Worker Populations. The study includes 85,642 film-badge monitored workers with a combined total of 2,976 cancer cases. Of the total, 35,868 were from the Hanford site (1,907 cancer cases), 22,239 workers from the Oak Ridge National Laboratory (430 cancer cases), 14,611 workers from the Oak Ridge Y-12 facility (294 cancer cases), 7,524 workers from the Oak Ridge K-25 facility (197 cancer cases), and 5,400 workers from the Fernald facility (1,069 cancer cases).

Worker Exposure Data. The study focuses primarily on external penetration radiation data with over 1.3 million film badge records analyzed.

Results. *From each study cohort there was evidence of a risk of cancer related to dose, and evidence that the extra radiogenic cancers had the same overall histological manifestations as naturally occurring cancers and were largely the result of exposures after 50 years of age causing deaths after 70 years. There were, however, significant differences between the five sets of risk estimates.... Although risks of cancer in nuclear*

⁶National Economic Council Occupational Illness compensation for Department of Energy Contractor Personnel, Report of Task Group 1, (DRAFT) January, 2000 December 23, 1999

workers were appreciably higher than estimates based on cancer experiences of survivors of the atomic bomb, some uncertainties remained as there were non-uniform standards of dosimetry at nuclear sites. The differences between nuclear workers and survivors of the atomic bomb were largely the relations between age at exposure and the risk of cancer being totally different for workers and survivors and, the occupational data, there were no signs of special risks of leukemia found in atomic bomb data and other studies of effects of high doses.@

Discussion. *AThe results of the present analysis are difficult to reconcile with the assumption that the cancer experiences of the atomic bomb survivors are a reliable source of risk estimates for nuclear workers... Failure to make any allowance for effects of age at exposure is clearly the reason why both Gilbert et al and analysis of Hanford data, and the IARC analysis of data from the United States, Canada and Britain, failed to find any evidence of extra radiogenic cancers. For recognition of necessarily small risks of cancers from strictly controlled doses of nuclear workers it may also be important to know where and when the doses were recorded....@*

23. Study. E. Cardis, E.S. Gilbert, L. Carpenter, G. Howe, I. Kato, J. Fix, L. Solomon, G. Cowper, B.K. Armstrong, V. Beral, A. Douglas, S.A. Fry, J. Kaldor, C. Lave, P.G. Smith, G. Voelz, and L. Wiggs, *Combined Analyses of Cancer Mortality Among Nuclear Industry Workers in Canada, The United Kingdom and the United States*, International Agency for Research on Cancer, World Health Organization (IARC Technical Report No. 25, Lyon, 1995).

Worker Populations. The study includes a total of 95,673 workers with a combined total of 15,825 deaths identified. Of the total, 32,595 workers were from Hanford (6,445 deaths), 6,638 workers were from Rocky Flats (587 deaths), 6,591 were from Oak Ridge National Laboratory (1,246 deaths), 9,494 were from Sellafield, UK (2,027 deaths), 29,000 consisted of Other UK workers (4,629 deaths), 11,355 workers were from Atomic Energy of Canada Limited (AECL) (891 deaths).

Worker Exposure Data: The study focused primarily on external penetrating radiation data collected from film badge readings. Most of the dose (98%) was received by men, 77% before the age of 50 and 63% before 1970. The distribution of doses was very skewed: 85% of the workers had received cumulative doses below 50mSv and less than 1% and 0.1% respectively had doses greater than 500 mSv and 1 Sv. In contrast, 9% of the atomic bomb survivors received doses greater than 500 mSv and 4 % received doses above 1 Sv. For comparison, the current ICRP recommendations are to limit occupational doses to 100 mSv over five years (not to exceed 50 mSv in one year) and doses to the public to 1 mSv in one year.

Results. *A There was little evidence of an association of all cancer mortality with cumulative radiation dose...Among single cancer types, mortality from leukemia excluding CLL [chronic lymphocytic leukemia] was significantly related to radiation dose,... as was mortality from multiple myeloma. Non-significant positive associations ($p < 0.2$) were observed for cancers of the rectum, pancreas, larynx and uterus, excluding cervix.... The majority of the cancer deaths occurred in men. For all cancers excluding leukemia, a marginally significant association ($p = 0.06$) was observed among ORNL workers. Significant associations were seen in leukemia excluding CLL among Sellafield*

workers ($p=0.012$, based on 10 deaths) and AECL workers ($p=0.009$, based on five deaths). A significant association was also seen for multiple myeloma ($p=0.046$, based on seven deaths) among Sellafield workers... When cancer as an associated cause of death was included, the excess relative risk of death from all cancers, excluding leukemia increased from -0.07 to 0.01 per Sv (90% CI...) For leukemia ...the effect was to reduce the excess risk from 2.21 to 1.78 per Sv (90% CI)... Adjustment for duration of employment at Hanford only or in all facilities increased the excess relative risk for all cancers excluding leukemia to 0.03 and 0.08 per Sv respectively. For leukemia [other than CLL] adjustment at Hanford increased the estimate to 3.363 per Sv, while adjustment in all facilities reduced it to 1.72 per Sv ...As the lag period used went from zero to 20 years, the estimated relative risk of death from all cancers excluding leukemia increased monotonically from -0.021 per Sv to 0.14... The excess relative risk for leukemia [other than CLL] also increased from 1.89 to 5.13 per Sv. ...@

Discussion. The risk estimate for leukemia obtained from nuclear industry workers data was 1.6 times higher than that of the a-bomb survivors based on a linear quadratic model (1.42 per Sv) and 0.60 times that based on a linear risk model (3.67 per Sv). The confidence intervals for the workers estimate was relatively wide, however, and ranged from 0.03 to 1.6 times for the linear estimate based on the atomic bomb survivors. [Comparisons of nuclear workers with A-bomb survivors, however, are fraught with complications because of the wide differences in the populations and the circumstances of exposure. Adult nuclear workers were mostly screened for good health prior to being hired and received chronic and multiple radiation and chemical exposures in industrial settings. A-bomb survivors of all ages received a single, large and prompt exposure under wartime conditions to ionizing radiation from a nuclear weapons explosion that created severe catastrophic consequences, above and beyond those created from radiation exposure.]

24. Study. E.L. Frome, D.L. Cragle, J.P. Watkins, S.Wing, C.M. Shy, W.G. Tankersley, and C.M. West, *A Mortality Study of Employees of the Nuclear Industry in Oak Ridge, Tennessee*, Radiation research, 1997, 148:64-80.

Worker Population. 106,020 workers employed at four federal facilities in Oak Ridge between 1943 and 1985 (Tennessee Eastman Y-12 facility, the Y-12 weapons facility, the K-25 Gaseous diffusion plant, and the X-10 Oak Ridge National Laboratory). Mortality data is comprised of 27,982 deaths collected through 1984.

Exposure Data: For workers at ORNL external penetrating radiation was measured by film badges. By 1948, over 98% of the employed workers were monitored and by November 1951 all ORNL workers were required to wear individual dosimeters. Employees at the Tennessee Eastman (TEC) facility were exposed to uranium-238 and uranium-235. Workers at the Y-12 weapons plant handled various compounds of uranium-235 and uranium-238 and were exposed to external penetrating radiations as well as internal exposures. Other agents used at Y-12 include solvents, machine oils, mercury, lead and beryllium. K-25 workers were exposed to external penetrating radiations from uranium isotopes and internal alpha and other radiations deposited in the body. (The presence of fission products from recycled uranium was not considered in

this study). Other agents to which workers were exposed include epoxy resins and hardeners, metallic nickel, uranium hexafluoride (UF-6), insoluble uranium oxides, hydrofluoric acid, solvents and a variety of chemicals, especially fluorocarbons.

Results. *All-cause mortality and all cancer mortality were in close agreement with national rates. The only notable excesses occurred for white males for lung cancer [SAR= 1.12, 1,568 deaths). A more detailed analysis revealed substantial differences in death rates among workers at the Oak Ridge Plants. Evaluation of internally adjusted log SMRs using Poisson regression showed that workers employed only at the Tennessee Eastman Corporation or K-25 and at multiple facilities had higher death rates than similar workers employed only at X-10 or Y-12, and that the differences were due primarily to non cancer causes. Analysis of selected cancer causes for white males indicated large differences among workers at different facilities for lung cancer, leukemia and other lymphatic cancer. Dose-response analyses for external penetrating radiation were limited to a subcohort of 28,347 white males employed at X-10 or Y-12...There was a strong Ahealthy worker effect@ in this subcohort... For external radiation dose with a 10 year lag, the excess relative risk was 0.31 per Sv for all causes and 1.45 per Sv for all cancer. The estimated relative risk for leukemia was negative but imprecisely determined.@*

Discussion. All cause mortality rates for Oak Ridge workers are unusually high because workers in large industries more often than not show a Ahealthy worker effect.@ One possible explanation is the large proportion of male workers who were hired at young ages during the World War II period B and who worked for a short time. Monthly paid workers had substantially lower mortality than weekly or hourly workers which is in agreement with other occupational studies. This study also suggests that there are differences in dose response between worker cohorts in the same location followed over about the same period and that these differences are associated with measurement issues. Specifically, dose response associations are stronger for X-10 workers, the population with more complete external radiation monitoring.

25. Study: Ethyl S. Gilbert, Donna L. Cragle, and Laurie D. Wiggs, Updated Analysis of Combined Mortality Data for Workers at the Hanford Site, Oak Ridge National Laboratory, and Rocky Flats Weapons Plant, Radiation Research, 1993, 136:408-421.

Worker Populations. The study included 32,643 workers from Hanford, 6,348 workers at the Oak Ridge National Laboratory, and 5,952 workers at the Rocky Flats facility. Mortality data was updated to 1986 for Hanford, 1984 for ORNL and 1979 for Rocky Flats.

Exposure Data: This study focused entirely on external penetrating radiation. No internal dose data were considered, nor were chemicals and other hazardous materials considered.

Results. *A For leukemia the combined excess relative risk estimate was negative (-)1.0 per Sv). And confidence limits excluded risks that were more than slightly larger than those forming the basis of ICRP recommendation. For all cancer except leukemia, the excess relative risk estimate was 0.0 per Sv, but confidence limits indicated consistency with estimates several times those forming the basis of ICRP recommendations. Of 24*

cancer types tested, 12 showed positive correlations with radiation dose and 12 showed negative correlations, as would be expected by chance fluctuation. Cancer of the esophagus, cancer of the larynx, and Hodgkin=s disease showed statistically significant correlations with radiation dose ($p < 0.05$), but these correlations were interpreted as likely to have resulted from bias or fluctuation. Evidence of an increase in excess relative risk with increasing age at risk was found for all cancer at both Hanford and ORNL and both populations showed significant correlations of all cancer with radiation dose among those 75 years and older.@

Discussion. *ACaution is required in interpreting these comparisons as confidence intervals do not include uncertainty resulting from confounding that has not been adjusted for, and possible biases and uncertainties in dosimetry. ICRP estimates were based on doses to bone marrow and other organs. Recorded dose estimates for workers probably overestimated doses to these organs and thus worker-based risk estimates may need to be increased for appropriate comparison with ICRP estimates. Also, there may be other dosimetry biases, especially exposure received in early years and for exposure received by Rocky Flats workers.@ [Since the publication of this study similar findings of a dose-response relationship between cancers of the esophagus and Hodgkin=s disease were found among Los Alamos workers (see Study No. 8) Excess Hodgkin=s Disease was also reported in the preliminary study of Portsmouth workers (see Study No. 15). Also, excess cancer of the esophagus was reported among workers at the Mallinkrodt facility (see Study No.10.)]*

26. Study. Elizabeth A. Dupree, Janice P. Watkins, J. Nicholas Ingle, Phillip W. Wallace, Charles M., West, and William G. Tankersley, *Uranium Dust Exposure and Lung Cancer Risk in Four Uranium Processing Operations, Epidemiology*, July 1995, 6:4.

Worker populations. 787 lung cancer cases with matching controls based on deaths collected to 1983 from workers at the Fernald, Ohio uranium foundry, The Malinkrodt uranium facility (MCW) in Missouri, The Tennessee Eastman (TEC) facility and the Y-12 weapons facility.

Exposure Data. Uranium exposures to the lung were estimated for each individual on an annual basis. For the Fernald, TEC and MCW, uranium air monitoring data were the basis of internal radiation doses. Annual lung dose estimates for Y-12 workers were based on uranium whole body counting and urinalysis results from personal monitoring. External whole body doses were determined on an annual basis for individual workers at Fernald, MCW and Y-12. No such data was available for TEC. Less than 30% of the population was monitored for external radiation. Prior to 1960 the majority of Y-12, MCW and Fernald workers were not monitored for external radiation.

Results. *AWe examined the relationship between uranium dust exposure and lung cancer mortality among workers employed at four uranium processing and fabrication operations....Odds ratios for lung cancer mortality for seven cumulative internal dose groups did not demonstrate increasing risk with increasing dose. We found an odds ratio of 2.0 for those exposed to 25 cGy and higher, by 95% confidence interval of 0.20 to 20 showed great uncertainty in this estimate. There is a suggestion of an exposure effect for workers hired at age 45 years or older. Further analyses for cumulative external doses*

and exposures to thorium, radium and radon did not reveal any clear association between exposure and increased risk, nor did dichotomizing workers by facility.@

Discussion. The current study differed from earlier ones in a number of ways. For instance, this study required a minimum employment of 6 months as contrasted with 30 days in previous studies and included twice as many cancer case. Several shortcomings of this study, including possible dose misclassification and potential exposure to other lung carcinogens, might have precluded finding an association between radiation exposure and lung cancer.

27. Baruch Gold and Ronald Kathren, *Causes of Death in a Cohort of 260 Plutonium Workers*, Health Physics, September 1998, 75:3, 236-240.

Worker Population. 260 workers who participated in the U.S. Transuranium Registry where they voluntarily donated their bodies for post mortem analysis for plutonium distribution in human tissue. The workers were from Rocky Flats, Hanford, Los Alamos, Oak Ridge, Mound and the Savannah River Site.

Exposure Data: Plutonium autopsy samples.

Results. *A In reviewing the causes of death among this biased cohort of 260 deceased registrants as presented ...There are however, four specific solid cancers that merit further attention because of their known association with exposure to ionizing radiation, especially plutonium and americium: lung carcinomas (28 cases), mesothelioma (6 cases) and osteosarcoma (1 case)...The number of lung cancer deaths is not extraordinary... Pleural mesothelioma is a well recognized disease associated with asbestos exposure... Despite the linkage of plutonium and americium exposure in experimental animals with osteosarcomas... only a single case ... was observed. This is well within the range for a normal population of this size....Of seven deaths attributable to neoplasia of the brain ...six neoplasia derived from neopithelial tissue...All six.... were active or former workers at the U.S. department of Energy=s Rocky Flats Facility...Clearly this observation is unlikely to be attributable to bias.*@

Discussion. This study is openly recognized by the authors as being flawed by virtue of its small size and the self selection by cohort members.