Conf-8110126--5

81-20 Internat meetg Lake Geneva

MORTALITY AMONG MALE WORKERS AT A THORIUM-PROCESSING PLANT*

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CONF-8110126--5

DE83 009639

ABSTRACT

The long-term health effects of exposure to thorium are of interest mainly because of the possible increased use of thorium as an energy source in reactors using ^{232}Th to produce ^{233}U. Mortality is described in a cohort of 3039 men who were employed between 1940 and 1973 at a company involved in the production of thorium and rare earth chemicals from monazite sand. Based on deaths ascertained by the Social Security Administration and using mortality rates for U. S. white males, the standardized mortality ratio (SMR) for all causes was 1.05. SMR's were high for cancers of the lung (1.44), rectum (1.90), and pancreas (2.01), and for motor vehicle accidents (1.64). A subgroup of 592 men who worked for one year or longer in selected jobs (laborer, operator, maintenance) was followed up more intensively. SMR's were high for both lung cancer (1.62; 95% CL = 0.78 and 2.98) and pancreatic cancer (4.01; 95% CL = 1.30 and 9.34). The higher proportion of smokers in this subgroup relative to U. S. males could have explained at least part of

*Work performed under the auspices of the U. S. Nuclear Regulatory Commission and the U. S. Department of Energy.

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the excess mortality from lung cancer. Continued follow-up of the cohort in morbidity and mortality studies is needed to evaluate further these possible long-term effects of exposure to radioactivity and chemicals in the thorium extraction process.

INTRODUCTION

There have been few studies of the possible health effects of exposure to thorium, as involved in the milling and processing of monazite ores. The possibility of increased use of thorium as an energy source (i.e., in reactors using ^{232}Th to produce ^{233}U) makes the results of such studies of potential relevance (Ri78). The radiological hazards of thorium mining and milling to surrounding populations also are under study (Mey79), and it is noteworthy that coal-fired power plants release thorium (and other primordial alpha-emitting radionuclides) into the environment (McB78).

Concern about the possible biological effects of thorium is based on its radioactivity, although the specific activity of thorium-232 is very low (0.11 μCi/g). Thorium-232 is the parent of the naturally occurring 4n decay series, which includes radium-228, thorium-228, radium-224, thoron (radon-220), and radioactive isotopes of four other elements (Figure 1). The total energy of the six alpha particles emitted in the series per parent disintegration is nine times that of thorium-232 alone, and numerous gamma rays are emitted during decay of daughter products, including the very penetrating 2.61-MeV gamma rays from thallium-208. The radioactive properties and biological behavior of thorium and its daughter products in man have been reviewed recently by Rundo (Ru78).

Albert et al. (Al55) reported on an industrial hygiene and medical survey of workers at a thorium refinery in Illinois. There was little evidence for unusual health problems in a small group of long-term employees, based on physicians' reports and on medical examination; chest X-ray films from four workers, however, showed evidence suggestive of early pneumoconiosis. An industrial hygiene survey of Brazilian workers employed in the milling of monazite sand disclosed a small uptake of thoron daughters and evidence for an increased frequency of chromosomal aberrations in peripheral lymphocytes (Co75).

Since thorium and its daughters are radiologic hazards, lung cancer is of particular interest in studies of thorium workers, especially in view of findings on uranium miners exposed to radon gas (Lu69;Ar74;Ku79) and on animals exposed to plutonium and thorium compounds (Le70;Ba73;Ba74). Cancers of bone and liver are also of interest in view of the results of animal experiments involving plutonium exposure. Cancer and other diseases of blood-forming organs also deserve attention in view of data on humans injected with thorium dioxide (Thorotrast) (Da74;UN77).

Due to uncertainties regarding the metabolism of inhaled and ingested thorium and its daughters, as well as potential exposures to other toxic substances involved in thorium processing, other diseases should be examined in mortality and morbidity studies of thorium workers. Diseases of the respiratory system are of particular interest because of the potential for inhalation of monazite sand and thorium dust in thorium processing (Al55), and because inhalation of plutonium and intratracheal administration of thorium compounds nave resulted in pulmonary disease in animals (Le70;Ba73).

In this report, data are presented on mortality among male workers employed in the production of thorium and rare earth chemicals at a single company. The principal raw material was monazite sand, a rare earth phosphate which typically has a composition of about 20% cerium, 20% other rare earth elements, 4% thorium and 0.3% uranium by weight (Al66).

MATERIALS AND METHODS

Definition of population

The population consisted of employees of a thorium-processing plant in Illinois. The parent company was formed in 1902 in Chicago and began manufacturing incandescent mantles for gas lamps with imported thorium and cerium nitrates. During World War I, the company started its own chemical processing operations to extract thorium and rare earth chemicals from monazite ores. In 1932, the chemical plant was moved to West Chicago (a small, semi-rural town) where it remained until its closing in 1973. Thorium mantles were manufactured at the same site from 1936 to 1947.

Copies of all available records of employees at the company have been obtained, covering the period from 1925 to 1973. A total of 3362 men and 722 women were identified as having worked at the West Chicago plant (St80). However, records prior to 1940 were incomplete and did not contain social security numbers and personal information (i.e., full name and birth date) sufficient for follow-up. Personnel records with social security number and date of birth were found only for employees who worked in 1940 or later. For those hired earlier and still employed in 1940, this information appears to have been filled in retrospectively.

The majority of females were involved in the production of incandescent gas mantles. Due to the small number of females and the unknown, but probably small exposures to thorium involved in mantle production (Ev40), the present report was limited to analyses of male workers. Since determination of vital status in this study depended mainly on the results of searches conducted by the Social Security Administration (SSA), the study group was limited to 3039 (of the 3362) men whose Social Security number, hiring date, and year of birth were known and whose Social Security number, obtained from company records, matched with that in SSA records.

Job classifications and levels of exposure to thorium

Job classifications in broad categories were available for the majority of workers and were used in the present analyses, along with duration of employment, to provide information relevant to exposure to thorium. An industrial hygiene survey of this plant in 1952 (Klev53;Al55) included collection of data on thorium dust and thoron, with estimates of exposure. Table 1 shows some of the data collected in this survey and a grouping of job titles by level of exposure to thorium dust. Survey meter readings indicated that radiation levels of 0.5 to 5 mR per hour were common at locations where thorium was processed or stored. Company records on individuals rarely contained information on specific job type or work area. As with studies of workers in other industries, "laborers" worked in many areas of the plant that differed in air levels of thorium dust and thoron. Table 2 shows the distribution of the 3039 males according to job classification.

Prior to analysis, the study group was divided into subgroups according to year of first employment at the company. Another subgroup was selected for more intensive follow-up based on two criteria: (1) job classification (i.e., laborer, operator, and maintenance), and (2) length of employment (one year or longer). This group of 592 men has been followed up intensively for ascertainment of vital status and for purposes of a morbidity study using a health questionnaire and medical examination. The mortality of this group was examined separately, using various sources of data on vital status (as described below).

Follow-up. According to SSA records, 511 of the 3039 men had died as of 1975 or 1976 (two separate searches were conducted). For most of the 511 decedents, a copy of the death certificate was obtained from state vital statistics offices. For some decedents, the state or country in which death occurred has not yet been ascertained, and search for certificates is continuing; other decedents (N = 6), for whom a certificate was not available, were determined to have been war-related deaths, and these have been included under "external causes" of death. Some 470 of the 511 deaths (92.0%) were of known cause. In the tables presented in this paper, no correction has been made for the non-availability of cause of death, but all deaths were included in the "all causes" category.

According to other studies (Ot76;Sh78), 92-94% of known deaths among male workers were reported as dead by the SSA. In this study, an estimate of completeness of reporting of deaths by the SSA was made based on the subgroup of 592 men followed up intensively. Using company records, postal questionnaires, drivers' license bureaus, and contacts with former co-workers, 92.5% (123/133) of known deaths (verified by death certificate and occurring before the 1975 or 1976 SSA searches) were also reported by the SSA after "nonmatches" (as defined above) were excluded.

Observed and expected numbers of deaths. Causes of death, as reported on death certificates, were coded by nosologists at the National Center for Health Statistics, according to the International Classification of Diseases (ICD), Adapted for Use in the United States, Eighth Revision (US68). Person-years of follow-up were enumerated from the year of first employment at the West Chicago plant to the year of death or of last search by Social Security (i.e., 1975 or 1976). For those hired before 1940, follow-up began in 1940 since all men had to have been still employed in 1940 in order to have been identified (see above). The method of computation of expected numbers of death has been described in detail by Monson (Mon74). Briefly, the person-years of follow-up of the study group were calculated in five-year age-time intervals, and multiplied by age- and cause-specific annual death rates (five-year averages) for U. S. white males. For each of 55 categories of cause of death for males (i.e., underlying cause reported on death certificates), the expected numbers in five-year age-time intervals were summed to provide a total cause-specific expected number. In the Monson computer program that was used (Mon78), 1970-1975 death rates were based on 1969-1971 rates from U. S. Vital Statistics reports. Because of rapidly changing rates in lung cancer mortality, we used 1970-1974 U. S. death rates for this cause of death for the 1970-1976 period. Eighth revision ICD codes were used for deaths observed over all time periods; this has little effect on the observed numbers of deaths, including lung cancer, as noted in other studies (Dol77). A correction was made for liver cancer, however, because of coding changes between the seventh and eighth revisions of the ICD (Kleb75).

Standardized mortality ratios (SMR's) were obtained by dividing the observed number by the expected number of deaths for each cause category. Confidence limits (95% interval) were calculated either on the basis of the Poisson or the continuity-corrected normal distribution, depending upon the observed number of deaths (Ha62).

RESULTS

Table 3 shows observed and expected numbers of deaths from selected causes, with emphasis on cancers. The overall mortality ratio (all causes, known or unknown) was 1.05 with 95% confidence limits (95% CL) of 0.96 and 1.15, while that for all cancers was 1.21 (95% CL = 0.99 and 1.48). For several cancer sites, standardized mortality ratios (SMR's) were greater than 1.00 -- e.g., for cancer of the rectum (1.90), pancreas (2.01), lung (1.44), skin (1.78), and bladder (1.55). Based on small numbers, mortality ratios for lymphosarcoma and leukemia were slightly greater than 1.00. There were no deaths from multiple myeloma in this population.

An excess number of deaths was observed for diseases of the respiratory system (i.e., 33 vs. 25.2 expected), including pneumonia (15 observed vs. 11.0 expected). Of the three deaths from "chronic interstitial pneumonia" (ICD code 517, not shown in Table 3), one had "chronic pulmonary fibrosis" listed as the underlying cause of death on the death certificate; carcinoma of the lung was listed as a contributory cause. One death was attributed to silicosis (ICD 515). All three deaths coded to "other diseases of the respiratory system" (ICD 519) were due to unspecified chronic lung disease. Expected numbers of deaths for the latter two categories were not available, since deaths for ICD 515 and 519 are not reported separately in U. S. vital statistics.

The number of deaths due to external causes was significantly greater than expected due to the category of motor vehicle accidents (38 observed vs. 23.2 expected). Other mortality ratios were based on small numbers.

Ascertainment of deaths in this population was not complete. If 93% of all deaths were identified, as found in a preliminary estimate for a subgroup of this population and in other studies, then the total number of deaths would have been 549 instead of 511 (SMR = 1.13; 95% CL = 1.04 and 1.23). Cause-specific SMR's may be adjusted on the assumption that the distribution of causes of death among unascertained deaths and among ascertained deaths without certificate was the same as that among the 470 deaths of known cause. Adjusted SMR's (and their 95% confidence limits) were: 1.68 (1.17 and 2.32) for lung cancer; 2.35

(1.15 and 4.26) for pancreatic cancer; 0.96 (0.84 and 1.09) for diseases of the circulatory system; and 1.53 (1.08 and 2.10) for diseases of the respiratory system. Thus, the adjusted SMR's for lung cancer, pancreatic cancer, and respiratory diseases were significantly different from 1.00.

Ethnic group. Since several studies have shown differences in cancer morbidity and mortality between U. S. whites and Mexicans (Men75), surnames were divided into Spanish and non-Spanish categories with the aid of a list of Spanish surnames from the U. S. Bureau of the Census (USB69). Mean age at employment (28.2 years) and mean year of employment (1956.9) for the 248 Spanish-surnamed men were similar to those for the 2791 non-Spanish-surnamed men (i.e., 29.8 years and 1956.2). For the 248 Spanish-surnamed men, 26 deaths were observed and 26.72 were expected on the basis of U. S. white male mortality rates. For seven of the 26 deaths, a death certificate copy was not yet available. Based on these limited data, lung cancer mortality was not increased (1 observed vs. 1.44 expected); there was one death from leukemia (vs. 0.23 expected) and four deaths due to motor vehicle accidents (vs. 1.85 expected). For the 2791 non-Spanish-surnamed men, results were generally similar to those obtained on the total 3039 men (see Table 3), of which they comprised the majority; e.g., the SMR for lung cancer was 1.49 (95% CL = 1.01 and 2.13), while that for pancreatic cancer was 2.14 (95% CL = 0.98 and 4.07). In this group of 485 deaths, 451 or 93.0% were of known cause. Since the proportion of workers with Spanish surnames was small and their inclusion had little effect on SMR's, this variable was disregarded in further analyses.

Some personnel records included an item on race, but this was usually left blank. According to statements of former company officials and workers, very few blacks were employed at the West Chicago plant; only five death certificates specified race as black. Thus, use of U. S. death rates for white males appeared justified.

Year of employment. SMR's for selected causes of death were obtained for two year-of-first-employment cohorts (i.e., 1940-1954 and 1955-1969). Excluded were 53 men who had started work before 1940; 22 (vs. 24.7 expected) of these 53 men had died and none of the deaths were due to lung cancer, pancreatic cancer or leukemia. Also excluded were 188 men first employed in 1970-1973; this group had ≤ 6 years of follow-up and only one death was observed (vs. 2.09 expected). The 1940-1954 and 1955-1969 groups were selected on the basis of sample size and also because the results of the industrial hygiene survey in 1952 are likely to be indicative of plant operations from the early 1940's to 1954, when a major addition to the plant was built. In 1956, the plant came under U. S. Atomic Energy Commission licensing requirements, whereupon personal dosimeters and periodic compliance inspections became mandatory.

Mean age at hire was similar for the two groups (Table 4). SMR's for overall mortality ("all causes") and for certain cancers were higher in the later (1955-1969) than in the earlier (1940-1954) group. Noteworthy were the high SMR's for lung cancer (2.09; 95% CL = 1.00 and

3.85) and cancer of the pancreas (5.82; 95% CL = 1.89 and 13.56) in the 1955-1969 group. All five deaths from leukemia occurred in the 1940-1954 group (SMR = 2.68; 95% CL = 0.87 and 6.24). The SMR's for diseases of the respiratory system did not differ between the two cohorts, nor did the ratios for motor vehicle accidents.

Subgroup of workers followed up intensively

As noted above, a subgroup of 592 men who worked for one year or longer in job classifications indicative of exposure to thorium dust was followed up more intensively than the remainder of the 3039 men. A total of 153 (25.8%) were known to have died by the end of 1978, 350 (59.1%) were known alive in 1976 or later by personal contact, and 48 (8.1%) others were known alive in 1975 or 1976 by Social Security records (i.e., working or receiving payments). The remainder (N = 41 or 6.9% of the 592 men in this subgroup) were treated as "lost to follow-up" as of the year of termination at the plant. SMR's for selected causes are shown in Table 5. The SMR for all cancers was 1.75 (95% CL = 1.26 and 2.39), and high SMR's were evident for cancer of the pancreas (4.13; 95% CL = 1.34 and 9.63), lung (1.68; 95% CL = 0.81 and 3.09), and several other cancers based on small numbers. The three deaths ascribed to cancers of the brain and central nervous system are noteworthy because of the small number expected in this group (0.62), and because one of these deaths (in 1968) was missed in the SSA searches (Table 3) and the other two occurred in 1975 and 1977. The SMR for diseases of the circulatory system was low, while that for motor vehicle accidents was high, as in the entire cohort (Table 3).

Information on smoking habits is essential in the analysis and interpretation of studies dealing with cancer mortality. In an ongoing study of morbidity in the subgroup of 592 men, 294 questionnaires have been obtained, with information on smoking habits and occupational histories. These 294 men represent 64.1% of the 459 who were alive (i.e., not known to have died) in 1976 when the morbidity study was initiated. Relative to U. S. males (Table 6), the thorium workers included a smaller proportion of men who had never smoked cigarettes, and a larger proportion of current smokers. The proportion of smokers in the total group of 592 men may have been greater than that reported here because of disproportionate loss of smokers (vs. non-smokers) from the original population due to death from diseases associated with smoking.

The possible effect of cigarette smoking habits on the SMR for lung cancer was considered. Under the assumption that all 298 men with unknown smoking habits (i.e., without questionnaire) were smokers, an approximate expected number of lung cancer deaths was calculated. The proportions of smokers in the U. S. in 1950-1954, 1955-1959, and 1960-1964 were based on a 1955 survey, while those for 1965-1969 were based on a 1966 survey (Ah70); results of 1970 and 1975 surveys (Na73;Na76) were used for 1970-1974 and 1975-1979, respectively. Age- and time-specific lung cancer death rates for U. S. smokers and non-smokers were calculated from age-specific relative risks for smokers vs. non-smokers obtained from Kahn (Ka66), by a method similar to that outlined by Buffler (Bu79). Men who were not current smokers according to questionnaire results obtained in 1976-1978, but who had stopped smoking after 1969, were considered smokers for purposes of this analysis. Person-years were not enumerated from 1940-1949 since lung cancer rates for smokers were not calculated before 1950. The SMR for lung cancer, based on crude adjustment by this method, could have been as low as 1.14 (10 observed vs. 8.76 expected), with 95% confidence limits of .55 and 2.10. Although it is unlikely that all men in the "unknown" category were smokers, under this extreme condition the SMR would still be slightly greater than 1.00.

DISCUSSION

This study group comprised a heterogeneous population of workers, undoubtedly exposed to widely varying levels of thorium dust, thorium daughters, and various chemicals involved in the production of compounds of thorium and of the rare earths. Individual exposures to specific compounds could not be estimated from available information; such exposures must have depended on specific job assignments and areas of the plant involved, work habits, and length and calendar years of employment. The majority of the study group worked in occupations (see Tables 1 and 2) involving higher levels of exposure to thorium and thoron than would be expected in the general population. Interpretation of available radioactivity data (see Appendix) suggests that all workers were exposed to "high" concentrations of lead-212, but only laborers and operators had occupational exposures to airborne thorium in excess of present maximum permissible limits.

The problem of suitable comparison groups for studies of occupational cohorts has been considered elsewhere (Go75). Cause-specific death rates for U. S. white males were used in this study; these rates are available in greater detail than rates for Illinois, and not all members of the cohort were long-term residents of Illinois. Also, U. S. rates were similar to rates for Illinois for many causes of death. For cancers at selected sites, ratios of age-adjusted death rates per 100,000 white males for 1950-1969 (i.e., the rate for Illinois divided by that for the U. S.) were: 1.05 for all cancer, 1.10 for stomach cancer, 1.21 for cancer of the rectum, 1.06 for cancer of the pancreas, 1.03 for lung cancer, 1.11 for cancer of the bladder, 0.99 for cancer of the prostate, 1.01 for leukemia and aleukemia, and 0.93 for Hodgkin's disease (Mas74). Thus, cancer death rates for Illinois white males were similar to, but generally slightly higher than, those for U. S. white males.

The limitations of using death certificates as an indication of the prevalence of specific diseases at death are well known. For lung cancer, comparison of death certificate data with autopsy findings has shown a high confirmation rate but lower sensitivity; for cancers of other internal organs (e.g., pancreas and liver), both sensitivity and confirmation rate are considerably lower (Ab71). Comparison of hospital record diagnoses with underlying cause of death (Wy76;Git79) has shown good agreement (i.e., 84% or higher) for lung cancer, as well as for leukemia and pancreatic cancer.

SMR's for some cause categories -- notably, infectious diseases and diseases of the circulatory system -- were less than 1.00 for the thorium workers. Low mortality ratios for such causes are not unexpected in occupational cohorts (Go75;Mon76) probably due to selection on past and present health. This "healthy-worker effect" is less likely to operate for most cancers than for cardiovascular diseases (McM76) since some of the latter or their risk factors can be detected through medical histories and examination. In contrast, for example, lung cancer is difficult to detect except in its later stages and the most important known risk factor (i.e., cigarette smoking) apparently has not been used as a basis for rejection of employment applications.

Many mortality ratios have been calculated and tabulated, and some may be expected to be high or low by chance alone. Interpretations about causality may be based on several criteria (Hi71), including the strength of the association, consonance with findings of other studies, and biological plausibility. We shall now discuss some findings on specific causes of death with reference to these criteria.

Lung cancer. There was a greater number of observed than expected deaths from lung cancer in the total study group (Table 3), with an adjusted SMR that was statistically significant. The overall excess was due largely, however, to a large number of deaths in the 1955-1969 year-of-employment group (see Table 4). The SMR for the earlier (1940-1954) group was lower (i.e., 1.26), and this group had about 21-36 years of follow-up. Also, three of the lung-cancer decedents in the 1955-1969 group died within five years (and seven died within 10 years) of first employment in the thorium-processing plant. Among white underground uranium miners, no significant excess lung cancer deaths occurred in the first five years after start of mining (Lu69), while in Indian uranium miners, none of the respiratory cancer deaths occurred prior to ten years after onset of mining (Wa75). Thus, the short intervals between employment and death of the thorium workers make it doubtful that there is an association with thorium processing. However, even an extreme adjustment for differences in smoking habits between a subgroup of thorium workers and the U. S. male population resulted in an SMR for lung cancer that was greater than 1.00, although the confidence interval was large.

Radiobiological data, especially estimated lung burdens of thorium and its daughters and of radiation doses to the lung, would be relevant to the interpretation of findings on lung cancer mortality in the population. In animal studies involving intratracheal administration of thorium compounds (Le70), most of the thorium was retained in the lungs. Radioactivity measurements in the present population suggest that thorium may be present in the chest region of many long-term workers (Ru79;Ru81). The results of further in-vivo studies in progress on larger numbers of former thorium workers and radiochemical studies of postmortem tissues should prove useful.

Cancer of the digestive system. Mortality ratios for cancer of the rectum and pancreas were high for the total group (Table 3). In the subgroup of 592 longer-term workers in the high-exposure (thorium and thoron) job categories, the SMR for pancreatic cancer was 4.13 (95% CL =

1.34 and 9.63) (Table 5). Smoking habits (Table 6) should be considered as a possible confounding factor, but the strength of the association with smoking is less for pancreatic cancer than for lung cancer (Dor59;Wi77).

The high SMR for pancreatic cancer may not indicate a causal association with exposure to chemicals involved in thorium processing. According to death certificates, only three of the nine pancreatic cancers were confirmed by autopsy findings and one other case was "probable". A possible host factor, previous diabetes mellitus (Cu77), was involved in one case. Cancer of the pancreas has been associated with radiation in several studies (UN77), but radiosensitivity is not high relative to other organs or tissues. Increased mortality from cancer of the pancreas has been reported among Hanford nuclear workers, based on small numbers (Gil79), but the role of exposure to chemicals needs further examination. An excess of pancreatic cancer deaths has been reported among chemists (Li69), and also among aluminum reduction plant workers (Mi79) exposed to various chemicals (fluorides, alumina, hydrocarbons and sulphur dioxide) in potrooms. In the present group, exposure to sulphuric and hydrofluoric acids, and rare earth chemicals (i.e., compounds of elements in the lanthanide series) must be considered; the toxicity of the latter compounds is not well known.

In conclusion, the high SMR's for cancer of the pancreas in the present study suggest the possibility of a real association with thorium processing which needs to be explored further in mortality and morbidity studies. The results of ongoing radiochemical studies on the distribution of inhaled thorium and rare earth chemicals in humans should prove useful in interpreting the findings of epidemiologic studies.

Leukemia and blood diseases. Leukemia and diseases of the blood and blood-forming organs are of interest because of the radiosensitivity of blood-forming tissues and the extensive literature on radiation-induced leukemias, as well as findings of studies on persons injected with Thorotrast (thorium dioxide). There was not a statistically significant excess of deaths from leukemias in the total study group (5 vs. 3.73, SMR = 1.35; 95% CL = 0.44 and 3.15) and no deaths from diseases of the blood and blood-forming organs.

All five deaths from leukemia occurred in the earliest year-of-employment cohort (i.e., 1940-1954; Table 4), and earlier workers may have been exposed to high levels of thorium since operations at the plant probably became cleaner over the years (Al55). One of the five leukemia deaths, however, occurred five weeks after the start of a 3-week period of employment. According to death certificates, one of the other four leukemias was chronic lymphatic. Chronic lymphatic leukemia has not been associated with radiation exposure in other studies (UN77), but lack of knowledge on the metabolism and distribution of inhaled and ingested thorium makes it difficult to eliminate the possibility of a relationship with thorium. In the subgroup of longer-term workers (Table 5), the number of leukemia deaths (2 vs. 0.91 expected) was too small to allow definitive conclusions.

In summary, there is no strong evidence for an increase in leukemia deaths associated with employment in this thorium-processing plant.

Diseases of the respiratory system. There was some evidence for increased mortality from diseases of the respiratory system in this population. After adjustment for unascertained deaths and missing death certificates, the SMR for respiratory diseases was 1.53 (95% CL = 1.08 and 2.10); the SMR was not higher in early workers (Table 4), however, or in longer-term workers (Table 5). The data on smoking habits in a sample of this population (Table 6) are relevant to the interpretation of these findings, in view of the well-established association between smoking and respiratory diseases. These considerations appear to preclude the need for speculation on the confounding effect of exposures to such substances as silica (known to produce pulmonary fibrosis); as noted above, only one death was due to silicosis. Questionnaires on respiratory diseases and symptoms, and smoking habits, from surviving workers will provide further data on the question of possible long-term effects of thorium chemicals on the respiratory tract.

External causes of death. An excess of deaths from external causes of death, attributable to one category (motor vehicle accidents), was found in the total group (Table 3) and in some of the subgroups compared. Inspection of the records showed no multiple deaths per accident and no obvious relationship to work times or the locale of the thorium refinery. Among foreign-born U. S. residents, persons born in Mexico have the highest motor vehicle accident death rates (Is68). In the present study, however, high mortality ratios for this cause were also found in non-Spanish-surnamed males, so ethnic group was not a factor. Also, motor vehicle accident death rates for the state of Illinois do not differ from those of the total U. S.

Lundin et al. (Lu69) reported a similar pattern of excess of violent deaths, including motor vehicle accidents (29 observed vs. 18.41 expected, SMR = 1.58; $p < 0.05$) among 3414 white underground uranium miners. Suicides were not increased in these miners or in the present group. These similarities may be fortuitous or may be related to socioeconomic and/or "lifestyle" variables. The apparently high frequency of cigarette smoking in both white uranium miners (Lu69), and the present group (Table 6), is noteworthy in this regard. Among Indian uranium miners, a group that uses little tobacco, no excess of deaths from violent causes was found (39 observed vs. 41.4 expected, 1960-1973) (Wa75). Drinking habits (alcohol consumption) must also be considered, since this variable is indicative of life style and is a risk factor in motor-vehicle accidents. However, alcohol is also a risk factor in cirrhosis of the liver and no excess of deaths from this disease was found (Table 3). Data on alcohol consumption are included in the ongoing morbidity study of this population.

In summary, high mortality ratios for a few cancer sites (i.e., lung and pancreas) were observed in this cohort of men exposed to thorium and rare earth chemicals. For lung cancer, however, at least part of the excess mortality could have been related to the smoking habits of this population; also, the mortality ratios were higher in later workers with shorter follow-up and probably lower levels of thorium exposure. The findings were not consistent with a strong relationship between employment at this thorium-processing plant and subsequent mortality from leukemia or from respiratory diseases, but morbidity from respiratory diseases is under investigation. Further follow-up of this cohort is needed, along with the studies of the metabolism of thorium (and its daughters) and rare earth chemicals.

ACKNOWLEDGEMENTS

Study of thorium workers was suggested by H. D. Bruner of the (then) U. S. Energy Research and Development Administration, and access to plant records was provided by officials of the thorium company.

The authors are indebted to Dr. Richard Monson of the Harvard School of Public Health for the computer program used for the analyses in this paper. Certain data used in this paper were derived from statistical information furnished by the Social Security Administration. The authors assume full responsibility for the analysis and interpretation of the data.

APPENDIX

For comparison with present day permissible limits for occupational exposure to airborne radioactivity, some discussion of the radioactivity data is necessary. Figure 1 shows the thorium-232 radioactive decay series.

At the West Chicago plant, measurements (see Table 1) were made by counting the alpha-particle activity of particulate matter retained on filters through which known volumes of air were drawn. In essence, the counting rates were measured twice: at about 10 hours after the end of filtration and at times long enough for almost complete decay of thoron daughters unsupported by radium-224 on the filter. The first count measured the alpha activity of bismuth-212 in transient equilibrium with 10.6-h lead-212, from which the concentration of lead-212 in the air samples was calculated. These concentrations were reported as "thoron" on the assumption that radon-220 and lead-212 in the air were in equilibrium. Except for very poorly ventilated rooms (less than one air change per day), it is more likely that the concentrations of radon were larger. So the "thoron" values in Table 1 actually represent lead-212, and comparison with the maximum permissible limit of 2×10^{-11} Ci/l for lead-212 (USNRC78) shows that all of the workers were exposed to higher concentrations of lead-212.

The amount of alpha-particle activity per disintegration of thorium-232 in "thorium dust" depends on how recently the thorium was purified and the degree of retention of thoron gas. Freshly purified thorium contains equal activities of thorium-232 and thorium-228, but the activity of radium-224 becomes equal to that of thorium-228 in about a month. The slow decay of thorium-228 is partially offset by growth of radium-228, and the ratio of thorium-228 to thorium-232 reaches a minimum value of 0.42 at about 4.5 years after a single purification and grows back to unity in about 50 years (Ru78). Thus, the portion of the thorium decay series from thorium-232 to radium-224 contributes from 1.8 to 3.0 alpha-particle emissions per disintegration of thorium-232.

Since the half-lives of thoron and its daughter products are relatively short, this portion of the decay series will contribute about 3Y alpha particle emissions per disintegration of the radium-244 present at any time, where Y is the fraction of thoron retained in the thorium material. Thus, a value of about 4 ± 2 may safely be assumed for the number of alpha-particle emissions per disintegration of thorium-232 in thorium chemicals or ores at the plant.

The maximum permissible limit is 6×6^{-11} µCi/ml for natural thorium, which is defined as equal activities of thorium-232 and thorium-228 (USNRC78). A reasonable approximation is to use a limit of 3×10^{-11} µCi/ml for thorium-232, which is equivalent to 266 ± 133 α dpm/m^3 of air on the basis of 4 ± 2 alpha particles per disintegration of thorium-232. Thus, only workers directly involved in the thorium extraction process had occupational exposures to airborne thorium (Table 1) in excess of the present maximum permissible limit.

The interpretations of radioactivity data in the above discussion have been confirmed by study of counting data on air filter samples from the thorium plant (Mau81).

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Table 1. Estimated exposure of male employees to thorium and thoron by job classification: group means of daily weighted average exposure, calculated from data of Klevin and Fresco (1953)

Job Classification(s)[a]	No. of persons	Thorium[b] (α dpm/m^3) (mean)	Thoron[c] (Ci/l x 10^{11}) (mean)
"Laborers" and "operators" in thorium extraction process	22	426	88
Other "laborers"	20	92	61
"Foremen"	2	120	86
"Maintenance and repair"	9	80	60
"Superintendents"	3	56	38
"Receiving and shipping"	1	12	12
"Control laboratory"	5	12	19
"Office personnel"	15	6	8
Other	7	29	35
Total personnel	84	151	52
(Maximum weighted exposure)		(2000)	(202)

[a]According to Klevin and Fresco (K153).

[b]Alpha-particle emissions per minute per cubic metre of air.

[c]Air concentrations, in units of 10^{-11} curies per liter, estimated from measurements of thoron daughter products.

Table 2. Distribution of male workers by job classification

Job classifications	Number	Percent
1. Laborer, operator	2383	78.4
2. Maintenance	307	10.1
3. Shipping, office, laboratory	311	10.2
4. Other, unknown	38	1.3
Total	3039	100.0

Table 3. Observed and expected numbers of deaths for selected causes among 3039 male thorium workers

Selected causes of death (with 8th Revision ICD codes)	Observed No.[a]	Expected No.[b]	SMR[c]	95% CL[d]
All causes	511	486.81	1.05	(0.96, 1.15)
All infective and parasitic (000-136)	3	8.67		
All cancer (140-209)	99	81.75	1.21	(0.99, 1.48)
Buccal cavity, pharynx (140-149)	0	2.76		
Digestive organs, peritoneum (150-159)	34	25.44	1.34	(0.93, 1.86)
Stomach (151)	6	5.92	1.01	(0.37, 2.20)
Colon (153)	7	7.40	0.95	(0.38, 1.96)
Rectum (154)	6	3.16	1.90	(0.70, 4.14)
Liver (155)	4	2.33		
Pancreas (157)	9	4.47	2.01	(0.92, 3.82)
Respiratory system (160-163)	32	22.97	1.39	(0.95, 1.95)
Lung (162)	31	21.56	1.44	(0.98, 2.02)
Bone (170)	1	0.58		
Skin (172, 173)	3	1.69		
Prostate (185)	5	5.83	0.86	(0.28, 2.00)
Bladder (188)	4	2.58		
Kidney (189)	2	1.96		
Brain, C.N.S. (191, 192)	0	2.68		
Thyroid (193) (1950 + only)	0	0.19		
Lymphosarcoma (200) (1950 + only)	3	2.07		
Hodgkin's disease (201)	1	1.60		
Leukemia, aleukemia (204-207)	5	3.73	1.34	(0.43, 3.12)
Diabetes mellitus (250)	6	7.01	0.86	(0.32, 1.87)
Diseases of blood (280-289)	0	1.32		
Diseases of circulatory system (390-458)	205	249.52	0.82	(0.71, 0.94)
Respiratory diseases (460-519)	33	25.18	1.31	(0.92, 1.83)
Pneumonia (480-486)	15	11.04	1.36	(0.76, 2.20)
Emphysema (492)	8	6.14	1.30	(0.56, 2.56)
Asthma (493)	1	1.28		
Digestive system (520-577)	24	23.69	1.01	(0.65, 1.50)
Ulcer (531, 532)	4	4.03		
Cirrhosis of liver (571)	11	11.16	0.99	(0.49, 1.77)
Genito-urinary system (580-629)	5	9.50	0.53	(0.17, 1.23)
External causes (800-998)	82	63.49	1.29	(1.03, 1.61)
All accidents	59	46.11	1.28	(0.99, 1.66)
Motor vehicle accidents (810-827)	38	23.24	1.64	(1.16, 2.23)
Suicide (950-959)	10	12.71	0.79	(0.38, 1.45)
Unknown cause	41			

Person-years of follow-up	54,614
Mean age at entry ± S.D.	29.6 ± 12.2
Mean year of entry	1956.2

[a]Deaths reported by the Social Security Administration (see text).

[b]Based on person-years of follow-up and on death rates for U. S. white males (Mon74;Mon78).

[c]Ratio of observed to expected deaths, or SMR (standardized mortality ratio).

[d]Confidence limits (95%) on the SMR's. When the observed number of deaths is less than five, SMR's and confidence limits are not provided.

Table 4. Mortality ratios for selected causes in two year-of-first-employment groups[a]

	YEAR OF FIRST EMPLOYMENT					
	1940-54 (N = 1352)			1955-69 (N = 1446)		
Selected causes of death	No. of deaths	SMR[b]	95% CL	No. of deaths	SMR[b]	95% CL
All causes	369	1.02	(0.92, 1.13)	119	1.23	(1.02, 1.48)
All infective and parasitic	2	[7.14]		0	[0.96]	
All cancer	67	1.10	(0.86, 1.45)	28	1.72	(1.14, 2.49)
Digestive organs	22	1.12	(0.70, 1.69)	10	2.35	(1.13, 4.32)
Stomach	3	[4.69]		2	[0.82]	
Colon	5	0.88	(0.29, 2.05)	2	[1.31]	
Rectum	5	2.03	(0.66, 4.73)	1	[0.51]	
Liver	3	[1.78]		0	[0.39]	
Pancreas	4	[3.36]		5	5.82	(1.89,13.56)
Lung	21	1.34	(0.83, 2.05)	10	2.09	(1.00, 3.85)
Prostate	3	[4.76]		0	[0.72]	
Bladder	3	[1.47]		1	[0.39]	
Lymphosarcoma	1	[0.69]		2	[0.52]	
Hodgkin's disease	1	[0.96]		0	[0.49]	
Leukemia, aleukemia	5	2.68	(0.87, 6.24)	0	[0.86]	
Diseases of circulatory system	159	0.82	(0.70, 0.96)	38	0.90	(0.64, 1.23)
Respiratory diseases	26	1.35	(0.88, 1.98)	6	1.31	(0.48, 2.86)
Pneumonia	13	1.52	(0.81, 2.60)	2	[1.89]	
Emphysema	5	1.09	(0.35, 2.54)	3	[1.24]	
Diseases of digestive system	18	1.04	(0.62, 1.64)	5	0.98	(0.32, 2.28)
External causes	53	1.34	(1.04, 1.77)	26	1.25	(0.82, 1.84)
All accidents	37	1.28	(0.90, 1.76)	20	1.34	(0.82, 2.06)
Motor vehicle	23	1.71	(1.08, 2.57)	15	1.73	(0.99, 2.80)
Suicide	6	0.73	(0.27, 1.59)	3	[3.90]	
Unknown cause	29			10		
Total person-years of follow-up	33,819			18,369		
Mean age at entry ± S.D.	31.1 ± 13.9			28.8 ± 10.7		
Mean year of entry	1947.6			1962.9		

[a]See footnotes to Table 3.

[b]Where the observed number of deaths is less than five, the expected number is given (in brackets) instead of the standardized mortality ratio (SMR).

Table 5. Observed and expected numbers of deaths among a group of 592 men who worked for one year or longer in selected job categories[a]

Selected causes	Observed No.[b]	Expected No.[c]	SMR	95% CL
All causes	153	123.10	1.24	(1.06, 1.45)
All cancer	38	21.69	1.75	(1.26, 2.39)
Digestive organs	13	6.82	1.91	(1.01, 3.25)
Rectum	1	0.85		
Liver	2	0.62		
Pancreas	5	1.21	4.13	(1.34, 9.63)
Lung	10	5.96	1.68	(0.81, 3.09)
Skin	1	0.40		
Brain, C.N.S.	3	0.63		
Lymphosarcoma	1	0.51		
Hodgkin's disease	2	0.34		
Leukemia	2	0.91		
Diseases of circulatory system	59	65.76	0.90	(0.69, 1.17)
Diseases of respiratory system	8	6.66	1.20	(0.52, 2.37)
Diseases of digestive system	6	5.90	1.02	(0.37, 2.22)
External causes	26	12.67	2.05	(1.33, 3.01)
Motor vehicle accidents	13	4.31	3.02	(1.61, 5.16)
Unknown causes	5			
Total person-years		10,621		
Mean age at entry ± S.D.		33.4 ± 13.1		
Mean year at entry		1955.7		

[a]Job categories involving the highest air levels of thorium and thoron (see text).

[b]Ascertainment of deaths was by various methods (see text).

[c]Person-years were enumerated from one year after start of employment to 1978 or (if earlier) to year of death or loss from follow-up

Table 6. Comparison of cigarette-smoking habits in U. S. males in 1974[a] and in a sample of the male thorium workers[b]

Age (yrs)		Current Smoker No.	Current Smoker %[c]	Former Smoker No.	Former Smoker %[c]	Never Smoked No.	Never Smoked %[c]	Total
25-44	Thorium	74	63.8	24	20.7	18	15.5	(116)
	U. S.		50.7		23.3		26.0	
45-64	Thorium	76	54.3	42	30.0	22	15.7	(140)
	U. S.		42.6		36.3		21.0	
65+	Thorium	12	34.3	12	34.3	11	31.4	(35)
	U. S.		24.8		41.6		33.6	

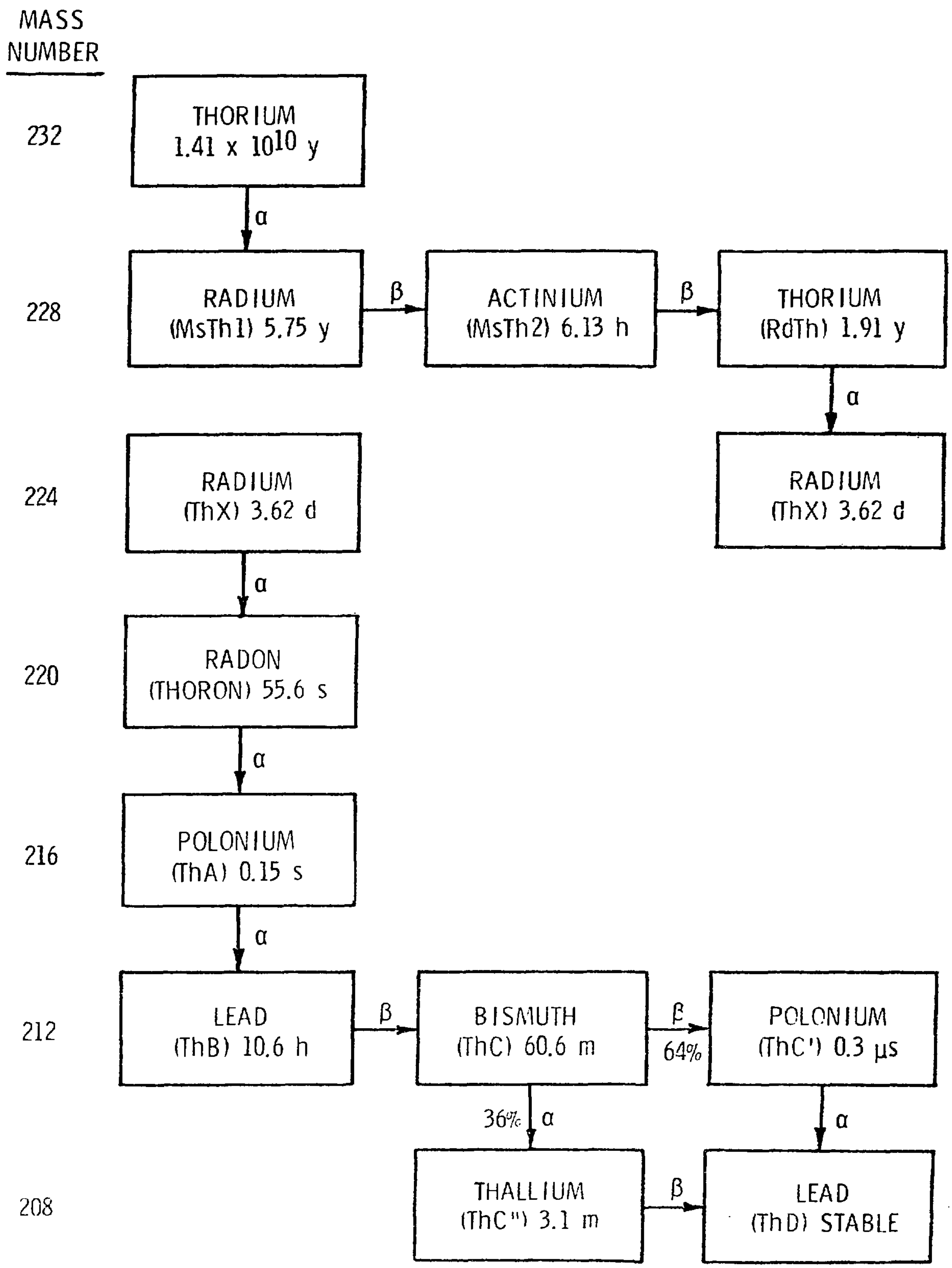
[a]According to the Health Interview Survey (Mos79).

[b]Three men less than 25 years old, at the time of questionnaire response, were excluded from the total of 294 respondents.

[c]Percent within age group.

Figure Legend

Figure 1 The thorium-232 radioactive decay series. The classical name, half-life, and principal decay mode are shown for each nuclide. (The box for radium-224 is repeated at the left to conserve space.)


MASS NUMBER
232
228
224
220
216
212
208
THORIUM 1.41 x 10^10 y
α
RADIUM (MsTh1) 5.75 y
β
ACTINIUM (MsTh2) 6.13 h
β
THORIUM (RdTh) 1.91 y
α
RADIUM (ThX) 3.62 d
RADIUM (ThX) 3.62 d
α
RADON (THORON) 55.6 s
α
POLONIUM (ThA) 0.15 s
α
LEAD (ThB) 10.6 h
β
BISMUTH (ThC) 60.6 m
β 64%
POLONIUM (ThC') 0.3 μs
36% α
α
THALLIUM (ThC") 3.1 m
β
LEAD (ThD) STABLE

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