Fernald Dose Reconstruction Methodology for the Post Special Exposure Cohort (SEC) Period, 1979-2006

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Overview

This paper provides information on the internal dose assessment methodology recommended for performing dose reconstructions for thorium and thoron at Fernald for the post SEC period, 1979-2006.

It is organized into sections and begins with a discussion of the Background information relevant to the SECs, followed by the Scope and Introduction. Regulations and Site Requirements and Radiological Controls are then presented. The Summary section provides the recommendations in table format, followed by a Discussion section, which details the recommendations. Example Dose Reconstructions are included to demonstrate application of the methods presented in this paper. A Conclusion section then follows. Attachments A-G contain supporting documentation and have been referenced within this paper.

Background

Three classes exist for the SEC at Fernald:

1) *All employees of the Department of Energy (DOE), its predecessor agencies, and their contractors, or subcontractors who worked at the Feed Materials Production Center (FMPC) in Fernald, Ohio, from January 1, 1968 through December 31, 1978, for a number of work days aggregating at least 250 work days, occurring either solely under this employment, or in combination with work days within the parameters established for one or more other classes of employees included in the SEC* (SRDB Ref ID: 127271). It was determined that NIOSH lacked the sufficient information to allow it to estimate with sufficient accuracy the potential internal doses from exposure to thorium, which employees at this facility may have been subjected (SRDB Ref ID: 129894).

2) *All employees of the DOE, its predecessor agencies, and their contractors and subcontractors who worked at the FMPC in Fernald, Ohio, from January 1, 1954, through December 31, 1967, for a number of work days aggregating at least 250 work days, occurring either solely under this employment, or in combination with work days within the parameters established for one or more other classes of employees included in the SEC* (SRDB Ref ID: 129226). It was determined that NIOSH lacked the sufficient information to allow it to estimate with sufficient accuracy the potential internal doses from exposure to thorium, which employees working at this facility may have been subjected (SRDB Ref ID: 127923).

3) *All employees of the FMPC in Fernald, Ohio, who were not employed by National Lead of Ohio, NLO, or the Department of Energy or its predecessor agencies, who worked at FMPC from January 1, 1951, through December 31, 1983, for a number of work days aggregating at least 250 work days, occurring*

either solely under this employment, or in combination with work days within the parameters established for one or more other classes of employees included in the SEC (SRDB Ref ID: 129226). It was determined that NIOSH lacked the sufficient information to allow an estimate with sufficient accuracy the potential internal doses from exposure to uranium, which employees of FMPC working at this facility may have been subjected. This dose reconstruction infeasibility for the period 1951 through 1983 applies only to subcontractors. NIOSH has access to an electronic data set that contains the results of the uranium urinalysis bioassay program for all the years of FMPC operations, and the overwhelming majority of employees of the prime contractor (National Lead of Ohio, later named NLO Inc.) have results in the bioassay data set. However, the data set does not contain bioassay results for employees of companies other than the prime contractor (i.e., non-prime contractor employees). NIOSH has obtained a limited number of bioassay samples from non-prime contractor employees through data captures, but cannot be certain that all non-prime contractor employees' bioassay data were retained by the site or captured by data capture efforts. Additionally, there are some reasons to conclude that the prime contractor did not consistently evaluate whether non-prime contractor employees should be monitored for radiation exposure because of the transitory nature of their work (SRDB Ref ID: 129961).

FMPC processed thorium intermittently through 1979, using several different chemical and physical processes. Additionally, FMPC utilized different monitoring programs for different time periods.

The premise of NIOSH's original proposal for reconstructing internal thorium exposures from 1954 -1967 was to use Exposure Studies that characterized exposures to various job categories in each building using a time-weighted airborne radioactivity concentration value called a daily weighted exposure (DWE). However, later review revealed that the daily weighted exposure values were not representative of exposures exclusively from thorium operations. The Advisory Board also concluded that such a dose estimate was not sufficiently accurate because the dose reconstruction method being proposed could not have been based on plausible circumstances (SRDB Ref ID: 127923).

From 1968 to 1978, FMPC used the Y-12 Mobile In Vivo Radiation Monitoring Laboratory (MIVRML) to monitor workers' exposure to thorium. NIOSH proposed to use data from the MIVRML to perform dose reconstructions. To do so, NIOSH performed considerable research to determine the algorithm that the MIVRML utilized to convert from a given mass of thorium to the activity of thorium and its daughters in units of milligrams for the years 1968-1978. Ultimately, the NIOSH Director and the Board determined that MIVRML results expressed as thorium milligrams could not be interpreted with confidence and that the reconstructed doses based on such an approach may not be done with sufficient accuracy. Therefore, the Board and the NIOSH Director concluded that it was not feasible to reconstruct with sufficient accuracy doses from internal thorium exposures for the years 1968-1978 (SRDB Ref ID: 129894).

In vivo examination services were available to all workers at Fernald, including prime contractor employees, DOE or DOE contractor employees, subcontractors, or those who visited the site to perform work for or, in conjunction with the prime contractor or DOE (SRDB Ref ID: 7870, p. 7). Beginning in 1979, the site's in vivo results were reported in terms of activity of Pb-212 and Ac-228. The remainder of this white paper focuses on thorium internal dose reconstruction methodology at Fernald, beginning in 1979.

Scope

The scope of this paper is limited to the internal thorium dose reconstruction methodology for the post SEC period (1979 - 2006). Thoron exposures are included. Internal exposures to uranium are beyond the scope of this paper, and, are not included in any further discussions, with the exception of customized breathing zone air monitoring results, which include uranium.

Introduction

According to a timeline of thorium processing operations (SRDB Ref ID: 42940), thorium processing began at Fernald in 1954 and continued through 1979. Fernald was the national thorium materials repository for the DOE starting in 1972. In 1988, an environmental assessment indicated that the inventory of thorium materials at Fernald consisted of approximately 1,100 metric tons (as thorium) of various thorium compounds. In 1988, the Plant 8 silo and bin contained approximately 175 metric tons of bulk thorium oxide materials plus other inert materials. The remainder of the thorium inventory was stored in various size containers in Warehouse Buildings #64, 65, 67, and 68 and as thorium nitrate in Tank 2 at the Pilot Plant. A small number of drums were in outside storage adjacent to Building #65 (SRDB Ref ID: 4611, p.10). The following table summarizes Fernald's stored inventory of thorium in 1987 (SRDB Ref ID: 84457, p. 3).

Location	Quantity	Weight
Plant 8 Silo and Bins	Bulk thorium oxide material & other inert materials	175 metric tons
Pilot Plant Tank 2	Thorium nitrate solution	9 metric tons
Building 64 (Plant 9 WH)	181drums	64.2 tons
Building 65 (Plant 5 WH)	5599 drums	1246.3 tons
Building 67 (Plant 1 Storage Bldg)	5992 drums	213.5 tons
Building 68 (Pilot Plant WH)	1317 drums	485.7 tons
PAD West of Building 65	212 (240 overpacked) drums	52.5 tons

WH = Warehouse

This includes a total of 13,329 drums and 2062.2 tons of thorium material (SRDB Ref ID: 84398, p. 13), plus the Plant 8 silo and bins material and the thorium nitrate solution in the Pilot Plant tank.

Various documents exist that discuss Fernald's thorium inventory and processing including, but not limited to: SRDB Ref ID: 29071, 84398, 84457, 85069, 83668, 41375, 44266 and 9012.

Post SEC Regulatory & Site Requirements

Implementation of DOE Order 5480.11, *Radiation Protection for Occupational Workers*, was the requirement document beginning January 1, 1989, with compliance required January 1990. This replaced DOE Order 5480.1A. Sites were required to submit a status report to DOE by January 27, 1989 with requests for exemptions and an implementation plan detailing how compliance would be achieved by December 31, 1989, (i.e., full compliance was not required until December 31, 1989), unless the implementation plan specified an earlier date (SRDB Ref ID: 108238, p. 5).

In June 1992, the DOE Radiological Control (RadCon) Manual was published and, in April 1994, Revision 1 of the DOE RadCon Manual occurred. DOE Order 5480.11 was cancelled September 29, 1995 and DOE required that each site develop their own Radiological Control Manual. Initially, the RadCon Manual was a guidance document, and later, a requirement. Fernald's Radiological Control (RadCon) Requirements Manual, Rev 0 was issued with an effective date of December 31, 1994 (SRDB Ref ID: 3269, p.3). The final rule for 10 CFR 835, *Occupational Radiation Protection,* occurred in January 1993 and became effective December 14, 1993; however, full compliance wasn't required until January 1, 1996.

In the site's Technical Basis for Workplace Air Monitoring Manual, Rev. 0, (August 1995), it was recognized that a technological shortfall existed in Fernald's internal dosimetry program with respect to thorium bioassay monitoring methods. It stated, "In the case of a technology shortfall, an enhanced workplace monitoring program shall be instituted to alert Radiation Protection personnel of areas with the potential to exceed 2 percent of the Annual limit of Intake (ALI) per 10 CFR835.403, based on contamination levels and potential release points" (SRDB Ref ID: 3545).

The Derived Air Concentrations (DACs) for Th-232 in DOE 5480.11 were the same as those listed in 10 CFR 835, namely 5E-13 µCi/ml (Class W) and 1E-12 µCi/ml (Class Y), (SRDB Ref ID: 108238, p. 63 and 32003, p. 3).

Post Production Thorium Activities

An inventory of thorium production orders shows that there were no orders after 1985 and only a few from 1979 -1985 (SRDB Ref ID # 9012). It is likely that most or all of these production orders involved just taking stored material out of a warehouse and shipping it to a customer. The occasional thorium repackaging effort (which typically involved placing eroding containers into larger containers) would have been short-duration, involved very few individuals, and those individuals were likely undergoing in vivo monitoring for potential uranium exposure during this period, so they would have had in vivo results.

In 1987, an environmental assessment for Fernald proposed the repackaging, overpacking and shipment of the thorium materials. The purpose of the proposed action was to stabilize deteriorating containers of thorium, and move the thorium from the site for long term retrievable storage under more appropriate conditions. Over the years of storage at Fernald, the environment had caused deterioration of the drums and containers, as well as the warehouses in which the material was stored (SRDB Ref ID: 4611, p.13). The 1987 environmental assessment identified 212 drums containing 241 smaller containers of thorium material stored outside of Building 65 and more than 13,000 containers stored in warehouse buildings #64, 65, 67, and 68. An estimated 175 metric tons of thorium material was in the Plant 8 bin and silo storage; it was estimated that approximately 2500 205-liter drums or 400 double walled boxes would be generated during removal (SRDB Ref ID: 4611, p.15).

Therefore, thorium work after processing ended at Fernald would have primarily been associated with efforts included in the "Three Project Plan," which involved improving the temporary storage conditions for thorium (SRDB Ref ID: 3559, p. 203). The total thorium inventory from the three projects was equivalent to approximately 15,000 fifty-five gallon drums (SRDB Ref ID: 85069, p. 4). The result of the three project plan was that thorium containers of material were repackaged and/or overpacked to meet retrievable storage criteria and Department of Transportation (DOT) shipping requirements. The thorium materials were then shipped to the Nevada Test site (NTS) retrievable storage facility (SRDB Ref ID: 4611, p.12).

Project 1

A detailed task force report on the thorium silo remediation/thorium material disposition was generated in 1986 (SRDB Ref ID: 28862). An Environmental Assessment on thorium handling was developed in 1987 (SRDB Ref ID: 29077). The first project addressed the bulk thorium materials in the Plant 8 silo and bins and was subcontracted to International Technology (IT) in September 1987. The timeframe for when actual work was being performed was November 1988 - March 1989. IT's scope of work included: Design/Installation/Operation of the Thorium Removal System, Plant 8 Silo and Bins Thorium Removal, and Packaging and Decontamination and Decommissioning of Plant 8 Thorium Handling System and Plant 8 Roof Refurbishing (SRDB Ref ID: 33877 & 29071). In September 1987, Fernald began the design and construction of the handling system necessary to remove and package the bulk thorium materials. Following construction, the removal, handling, and packaging of thorium began in November 1988. As the bulk materials were removed from the silo and bins, they were placed in double containment drums called overpacks (a 48-gallon drum is packaged inside a 55-gallon drum), inventoried and monitored. The drums were then stored in a new onsite warehouse located along the northern edge of the production area, away from daily plant operations. The overpacking portion of the project was completed in March 1989. The silo and bins were then to be decontaminated and demolished (SRDB Ref ID: 3554, p. 451).

Project 2

The second project involved the overpacking of the 241 containers (212 of the containers were drums) stored outdoors. The actual work was performed January - May 1990. As part of the second project, the design of a remote system for handling, identifying and overpacking the thorium drums and containers stored in warehouses and outdoors was completed in 1988. Purchase of the overpacking equipment began in early 1989. The training for this project was conducted August - December 1989 and included a variety of workers, such as: chemical operator, pipefitter, welder, electrician, oiler, millwright, radiation safety technician, industrial hygiene technician, maintenance supervisor, instrument mechanic, industrial mechanic, electrical maintenance supervisor, schedule analyst, safety engineer, safety and fire inspector, senior project engineer, planner estimator, and various technologists, technicians, supervisors (SRDB Ref ID: 44282). Each container was inventoried, weighed and scanned (to determine the percentage of thorium it contained), then placed in interim storage at Fernald (SRDB Ref ID: 3554, p. 451). This project was expected to be completed in March 1990; however, due to temperature restrictions and equipment malfunctions, completion of thorium overpacking did not occur until May 1990. As of April 30, 1990, one hundred seventy-five drums of thorium had been overpacked (SRDB Ref ID: 33893, p. 14).

Project 3

The third project involved the overpacking of 13,000 containers of thorium, which began in 1991. Project 3 was planned for 1991 - end of 1993. However, it was not completed as scheduled, leaving 5,600 drums to be over packed, as discussed below. The timeframe of this project was approximately 1991-2006. An evaluation for the thorium storage buildings was conducted in 1991, and identified that the Building 65 containers were in a severe state of deterioration with resultant leakage of material. This resulted in the evolution of the Thorium Overpacking Project (TOP), which was to safely and effectively overpack approximately 5,600 drums of thorium bearing materials into approved strong, tight containers in preparation for off-site shipment for final disposal at NTS. For the purposes of this paper, the TOP is considered to be a continuation of Project 3. The drum overpacking was accomplished through the implementation of a Remote Controlled Material Handling System (RCMHS) which included a mobile unit fitted with appropriate controls for remote operation, remote control command unit, handling attachments and visual monitoring system (SRDB Ref ID: 130104). On July 28, 1991, the overpacking and relocation of 35 thorium containers characterized as mixed waste to a RCRA warehouse was completed. Also completed were the necessary overpacking, relocation, and RCRA evaluation actions for all but 16 of 192 containers which required further characterization.

The characterization of the 16 remaining containers was scheduled to be completed by June 1992 (SRDB Ref ID: 3559, p. 90, 202-203). Between January 1, 1992, and April 1, 1993, more than 1,600 drums of thorium materials were shipped to NTS (SRDB Ref ID: 3569, p. 81). Overpacking in the Thorium Warehouse was completed in 1992. Also, thorium was repackaged and transferred to the (Old) Plant 5 Warehouse in the same year. Note that the Thorium Warehouse being discussed at this point is Building 64 and the building referred to as the (Old) Plant 5 Warehouse is Building 65 (SRDB Ref ID: 4611, p. 24 and 3563, p. 174). These movements were done to lower radiation exposures to site workers since fewer personnel entered the areas of the (Old) Plant 5 Warehouse. Plans were underway to consolidate all thorium into this warehouse pending approval for shipment to NTS (SRDB Ref ID: 3563, p. 178).

Overpacking in the Plant 1Thorium Warehouse was completed in 1993. The Pilot Plant Warehouse overpacking efforts were completed in 1992. The FEMP proposed to complete the overpacking in the (Old) Plant 5 Warehouse by the end of 1993 (SRDB Ref ID: 3563, p. 178). In 1993, three drums of thorium materials were shipped to NTS. Also in 1993, the site completed the overpacking of 6,100 drums of thorium materials and expected to have approval to ship those materials to NTS in 1994 (SRDB Ref ID: 3569, p. 81).

In 1994, the site shipped 750.4 drum equivalents of thorium material to NTS for disposal. Additional shipments were planned for 1995 (SRDB Ref ID: 3575, p. 91).

Almost 6,000 gallons of thorium nitrate, a contaminated acid waste stream, were treated and solidified safely in 1995. The final rinse of the thorium nitrate tank was completed November 9, 1995, less than two months after Chem-Nuclear, Fernald's subcontractor, began processing the material and six months after Fernald and Chem-Nuclear began designing the treatment system. During the project, 369 drums of solidified thorium cement were generated (SRDB Ref ID: 3578, p. 41). In 1995, the site shipped 776 drum equivalents of thorium material to NTS for disposal (SRDB Ref ID: 3578, p.104)

Fluor Daniel Fernald workers began packaging the remaining 5600 thorium drums from Project 3 on May 6, 1996. The project established multiple safety guidelines and compliance requirements to ensure safe operations and the safety of the workers. The project was more than halfway to the target to overpack 5,600 deteriorated drums of thorium for safe transportation and permanent, off-site disposal.

As of April 1, 1997, an estimated 4,489 drums had been overpacked. The two-year operation, targeted for completion in September 1997, was ahead of schedule. DOE and Fluor Daniel Fernald anticipated the project would be completed in the summer of 1997. The disposition of thorium was an ongoing effort since June 1992 (SRDB Ref ID: 3586, pg. 26). In 1996, Fernald shipped 2,172 drum equivalents or 46,101 cubic feet of thorium material to NTS (SRDB Ref ID: 3586, p. 93). In 1997, Fernald removed 3,400 containers of thorium material and shipped 10,875 drum equivalents, or 80,480 cubic feet of thorium material to NTS, completing the Thorium Overpack Project (TOP). Characterization of the remaining estimated 8,500 containers of thorium legacy waste at the site was initiated in 1997 (SRDB Ref ID: 3592, p. 54). The characterization documentation and formal RCRA waste determinations for the remaining estimated 8,500 containers of thorium legacy waste continued in 1998 (SRDB Ref ID: 3604, p. 51).

Plant 9 decontamination and dismantlement was completed in 1999. The subcontractor completed field work in February, including structural steel size reduction, decontamination, and demobilization. The project closeout report was submitted to the regulatory agencies and approved. The characterization documentation and formal RCRA waste determinations for the remaining estimated 8,500 containers of thorium legacy waste continued in 1999 (SRDB Ref ID: 3606, p.47, 52).

In 2000, over 6,000 of these containers were shipped to NTS (SRDB Ref ID: 9010, p. 47). Through the end of 2001, over 6,400 of these containers were shipped to NTS (SRDB Ref ID: 3516, p. 44). Through the end of 2002, over 7,100 of these containers were shipped to NTS (SRDB Ref ID: 126955, p. 51). Through the end of 2003, over 8,400 of these containers were shipped off-site for treatment, with subsequent disposal at NTS. Those containers included all RCRA hazardous thorium legacy-waste that had a scheduled milestone of December 5, 2003. This shipping effort removed approximately 1,500,000 pounds (681,000 kg) of thorium from the total site thorium inventory (SRDB Ref ID: 126956, p. 51). In 2004, Fernald shipped 4,274 pounds (1,940 kg) of mixed thorium waste to Envirocare of Utah, Inc. for treatment and disposal, and 21,192 pounds (9,621 kg) of non-hazardous thorium waste to NTS for disposal. At the end of 2004, there were only a few containers of thorium waste remaining on site (SRDB Ref ID: 129790, p. 45). In 2005, Fernald shipped 1,051 pounds (477 kg) of mixed thorium-contaminated oil to Envirocare of Utah, Inc. for treatment and disposal. At the end of 2005, there were only three containers of thorium-contaminated mixed waste remaining on-site (SRDB Ref ID: 129791, p. 48). With the completion of remediation, DOE completed the disposition of the containerized waste inventory. The last shipment of hazardous waste occurred October 2, 2006, ending hazardous waste management activities (SRDB Ref ID: 129793, p. 57).

Remediation of the Fernald site was completed on October 29, 2006, and the site was officially transferred into Legacy Management on November 17, 2006. The DOE's Office of Legacy Management and their Technical Assistance Contractor, S.M. Stoller Corporation, assumed full responsibility for operations at the Fernald site on November 17, 2006 (SRDB Ref ID: 129793, p. 15, 20).

Radiological Controls

The documentation from Projects 1, 2 and 3 demonstrate that the radiological protection program included the elements of today's standards. Procedures associated with thorium handling, training plans and rosters exist. Detailed technical reviews were conducted and adequate control measures appear to have been implemented. Memos describing events from daily thorium operations were reviewed. Radiological controls described within these documents include requirements for work permits, respiratory protection, shielding requirements, personal monitoring, bioassay, air monitoring requirements, etc. As Low As Reasonably Achievable (ALARA) principles were utilized.

The post SEC thorium processes appeared to be well planned and designed to minimize exposure to workers with adherence to regulatory requirements and the standards of the era. A detailed timeline of Fernald's post-production thorium activities is summarized in Attachment A.

Some examples of controls from Project 1 are:

Operational Safety Requirements (OSRs) for the removal of thorium handling system required that all radiological monitoring equipment be tested and calibrated before work began and to be recalibrated semiannually. In addition, Breathing Zone (BZ) air sampler pumps were required to be calibrated daily (SRDB Ref ID: 33881, p.25).

A Technical Summary of the Thorium Handling Project (SRDB Ref ID: 33896, p. 41) discusses that IT's BZ samples will be collected for a suitable duration to achieve the detection limits equal to the derived concentration guide specified for Thorium-232 and its daughter products in DOE Order 5480.11 and its revisions.

Thorium Repackaging Project included a review of IT's Radiological Safety Program due to a suspected thorium inhalation event (SRDB Ref ID: 33877).

A "Minor Event Report" of a thorium spill at the Plant 8 thorium silo, contamination survey and air monitoring report was documented (SRDB Ref ID: 33879).

IT generated a memo discussing problems associated with an open duct on the top of the Plant 8 thorium bin (SRDB Ref ID: 33880).

Some examples of controls from Project 2 are:

Memorandum of an Air sampling counting procedure associated with thorium repacking in 1989 (SRDB Ref ID: 33954) and another Memorandum on the Summary of Radiological Controls used in thorium repacking, 1990 (SRDB Ref ID: 33882).

OSRs for the removal and overpacking program (212 containers of thorium metals) in 1989 (SRDB Ref ID: 33959).

Various Standard Operating Procedures (SOPs) for thorium overpacking in 1989, including thorium drum handling procedures (SRDB Ref ID: 44281). Other SOPs and checklists associated with the thorium handling project in 1989 (SRDB Ref ID: 44272 through 44280).

Training plan for thorium overpacking of 212 drums (SRDB Ref ID: 44290).

Final Safety Analysis Report (FSAR) for thorium overpacking of 212 drums, 1989 (SRDB Ref ID: 4188).

In the SOP Radiological Controls for Repackaging Thorium, Rev 1, March 1990, the DAC for thorium-232 was noted to be 5.0×10^{-13} uCi/ml, also, "Before, at three month intervals during and at completion of the job, individuals working with thorium shall have *in vivo* lung measurements performed. Individuals whose work includes routine handling of thorium shall be required to submit background fecal samples prior to initiating work. Air sample results indicating a thorium inhalation in excess of 8 DAC hours (with the respiratory protection factor considered) shall trigger *in vivo* measurement and/or bioassay. Additional bioassay (including urine or fecal analysis) may also be required as determined by the responsible Radiological Engineer until the magnitude of the intake has been estimated, the individual may be restricted from Airborne Radioactivity Areas" (SRDB Ref ID: 33913).

Radiation exposure to workers during thorium operations was planned to be covered in a radiological safety work plan. Administrative controls for occupational exposure included personal dosimetry, health physics surveys, radiation protection procedures, and the use of protective clothing and respiratory protection, as required. These controls would limit radiation exposure to workers to as low as reasonably achievable within the DOE limit of five rem per year. The estimated whole body dose equivalent to the maximum individual of the public who resided at the site boundary at the point of maximum annual concentrations of thorium-232 was calculated to be 3.8×10^{-3} millirem in an environmental assessment. The same assessment determined that the total calculated dose equivalent to the maximum individual of the public using the 65-week life of the project was 4.9×10^{-3} millirem, with a committed dose equivalent to the bone surface of 3.4 millirem (SRDB Ref ID: 4611, p.55-57). Air samples were planned to have been collected during repackaging operations to document that personnel exposures were acceptable (SRDB Ref ID: 4611, p.20).

Some radiological controls identified in a 1990 memorandum on the thorium repackaging project were: "A new radiation work permit is required at the beginning of each shift. Access to the thorium repacking area will be controlled by an access control list. Only those who have completed thorium training will be allowed in the repackaging area. Each thorium operator is required to wear a BZ sampler at all times while he is inside the radiological barrier fence. Personnel who work inside the thorium repackaging area for greater than 30 minutes per day are required to wear an airline hood. Those who work for 30 minutes or less are required to wear a full-face respirator. The forklift operator is required to wear a PAPR half-face respirator while he operates the forklift. Personnel who enter the repackaging area must wear anti-C clothing complete with shoe covers, hood, and gloves which are taped at the wrist and the ankles. Background in vivo samples and fecal samples were taken for each operator prior to starting the operation and at three month intervals during the operation" (SRDB Ref ID: 33882).

The Fernald Internal Dosimetry Technical Basis Manual, December 31, 1990, states "The major potential source of exposure to thorium material at the FMPC is the repackaging of thorium drums. This operation is covered under the safety procedure, "Radiological Controls for Repackaging Thorium. All compounds of thorium at the FMPC are assigned to inhalation class Y" (SRDB Ref ID: 4145, p. 47, 48).

<u>Some examples of controls from Project 3 are:</u>

Radiological Controls for the Thorium Nitrate Solidification & Stabilization Project (draft) gave consideration to maintaining airborne radioactive material concentrations below maximum values of 0.1 DAC in the breathing zone of workers, with thorium-232 (Class W) identified as the radioisotope of concern for occupational radiation protection purposes. The DAC for Class W Th-232 is 5×10^{-13} µCi/ml, as listed in Appendix A of 10 CFR 835. Posting as an "Airborne Radioactivity Area" was required at 10% of this DAC. In addition to the monthly urine sampling requirement for this project, a base-line fecal sample was required of all personnel whom must enter the zone. Personnel Air Sampling (PAS) was required for all personnel whom must enter the zone (SRDB Ref ID: 32604).

Transmittal of Final Report for Thorium Nitrate Tank indicated that the DAC for Thorium-232 (Class W soluble) was applied for radiation protection purposes on this project. In addition, from Appendix A of 10 CFR 835, a DAC of 1.0 working level (WL) was applied for thoron progeny (SRDB Ref ID: 36159).

Information on Removal Action No. 9 Building 65 Thorium Overpacking Project (SRDB Ref ID: 130104).

Safety Analysis Report for the Warehoused Thorium Overpacking Building 65 (SRDB Ref ID: 3503).

Numerous documents exist which detail the planning involved in the thorium work, the follow-up, and the involvement of Radiological Controls from Project 3. Some of these documents include, but are not limited to a "Health Physics Plan for the TOP," Rev 2 (SRDB Ref ID: 132927), a memorandum on the "Updated Dose Estimate for the TOP" (SRDB Ref ID: 132929), and an "Airborne Contamination Control Implementation Plan for the TOP," Rev 2 (SRDB Ref ID: 132930).

"Note that the HIS-20 database was not implemented until the mid-1990s. Although thorium BZ samples were being collected as indicated in the control descriptions above, they are not reliably available in HIS-20 until 1995. However, in-vivo results for thorium workers are available for Thorium Overpacking Projects 1, 2, and 3."

Summary

The major Fernald thorium work and regulatory requirements post SEC period can be summarized as:

Project	Project Description	Timeframe	Regulatory Requirements
1	Overpacking Plant 8 and Silo thorium material	November 1988 - March 1989	DOE 5480.11 DOE 5480.1A
2	Overpacking 241 containers (212 were drums)	January 1990 - May 1990	DOE 5480.11
3	Overpacking 13,000 containers	1991 - 2006	DOE 5480.11 RadCon Manual 10 CFR 835

Thorium doses are recommended to be assigned as follows at Fernald:

Timeframe	In Vivo Data Exist (Yes/No)	Evaluation Method	Source/Basis
1979 - 1994	Yes	In Vivo Results	[a]LaBone documents
1979 - 1989	No	Coworker Data	[b]Thorium In Vivo Coworker Study
1990 - 1994	No	10% Th-232 Class W DAC	[c]Thorium Inh/Ing intake from air limit calculation (DOE 5480.11 & Project 2 documentation)
1995 - 2006	Yes - may use to decide if in vivo results reflect a lung burden that had been previously	BZ Air Monitoring results	10 CFR 835 compliance and thorium bioassay technology shortfall (SRDB Ref ID: 3545

	identified from earlier exposure. Positive in vivo is used in place of negative BZ results unless it is an artifact of an earlier detected lung burden. For in vivo results below MDA use BZ results. No – use BZ data		& HIS-20 database)

a. Evaluation of Fernald Ac-228/Pb-212 Chest Count Data, 04/18/2013, Activity Ratios for various types of Thorium, 06/21/2013, Approximate Evaluation of Pb-212 Chests Counts Following Intakes of Thorium, 07/19/2013, and Using Ac-228 and Pb-212 to Measure Intakes of Th-232, 09/18/2013, see Attachments B.1-4.
b. Thorium *In Vivo* Coworker Study (in development), Attachment C.
c. Thorium Inhalation/Ingestion intake from air limit calculation, Attachment D

The basis for these recommendations is described below, with the timeframes separated out.

Discussion

1979-1994

Chest count measurements exist in claimant's records during this timeframe and may extend beyond this timeframe. The evaluation of in vivo results uses ORAUT-OTIB-0060, "Internal Dose Reconstruction" (SRDB Ref ID: 29984) methods. If all in vivo results are negative, then only missed dose is assigned. Positive in vivo results are adjusted for bias by subtracting the bias values in the table below. The most claimant favorable absorption type is assumed.

The radionuclides that can be quantified with a chest count are Ac-228 and Pb-212. Thorium intakes are evaluated using Pb-212 values rather than the Ac-228 results because the Pb-212 results are considered more reliable for the calculation of Th-232 and Th-228 dose. The chemical separation history is normally unknown, therefore the default worst case material composition (triple-separated thorium with a Th-228:Th-232 disequilibrium ratio of 0.19:1) is assumed.

Detection Levels (DLs) were derived from Attachment B-1, *Evaluation of Fernald Ac-228/Pb-212 Chest Count Data, 04/18/2013,* as summarized below.

[a]Summary of Bias and DL for Ac-228 and Pb-212 (nCi) in Chest

Year	Pb-212 Bias	Pb-212 DL	Ac-228 Bias	Ac-228 DL
1979	-0.014	0.156	0.031	0.169
1980	-0.045	0.123	0.025	0.091
1981	-0.056	0.108	0.022	0.127
1982	-0.058	0.121	0.010	0.117
1983	-0.101	0.122	-0.008	0.097
1984	-0.089	0.111	0.001	0.079
1985	-0.086	0.117	0.017	0.102
1986	-0.085	0.128	0.020	0.114
1987	-0.047	0.123	0.008	0.106
1988	0.002	0.181	0.058	0.107
1989-1994[b]	0.072	0.21	0.182	0.55

a. DLs are equal to one-half of the Minimum Detectable Activity (MDA).
b. The basis for these values is described in SRDB Ref ID: 131224.

The in vivo results are evaluated using the following methodology:

1. Evaluate the Pb-212 chest burden (MDA/2 for missed or result adjusted for bias for fitted dose) with a Th-228 biokinetic model in IMBA. Use the annual DLs from the table to evaluate missed dose.
2. Multiply the calculated Th-228 intake rate by a correction factor of 1.1 (as applicable) and assign it as the intake rate of Th-228.
3. Divide the estimated Th-228 intake rate by 0.19 (based on the Th-228:Th-232 ratio of 0.19:1) to obtain the Th-232 intake rate. Since the thorium is assumed to be triple-separated, there is no associated Ra-228 with the thorium intake.
4. Evaluate the Ac-228 chest burden (MDA/2 for missed or result adjusted for bias for fitted dose) with a Ra-228 biokinetic model in IMBA and assign it as the intake rate of Ra-228. Note that since this is unsupported radium, it is not part of a mixture and therefore only assessed as absorption type M.

Notes to consider

The correction factor of 1.1 (based on the Th-228 approximation method) does not apply to underestimates. For overestimates, the 1.1 correction factor is applied. In order to apply the 1.1 correction factor, chronic intakes must be longer than 1 year and acute intakes must have the chest count taken more than 30 days after the intake. For best estimates, or if either of the time period scenarios are true, then a best estimate of the correction factor must be determined.

For best estimates of dose, Dose and Risk Calculation (DCAL) software is used to account for the independent kinetics of the thorium decay chain and the loss of Rn-220.

DLs from the table are used to evaluate chest count measurements, unless claim-specific chest count DLs exist.

Triple-separated thorium with a ratio of 0.19:1, Th-228:Th-232 is assumed, unless claim-specific information exists. For triple-separated thorium, there is no Ra-228 intake associated with the thorium intake. However, there is likely unsupported Ra-228 (not part of the thorium mixture) which is evaluated separately, as discussed in #4 above.

It is recognized that the assignment of thorium missed dose based on in vivo counts will result in high doses, which NIOSH doesn't believe occurred given the radiological controls in place at the time.

The assignment of thorium doses based on in vivo results includes the IT subcontractors who were involved with Plant 8 silo and bin remediation/thorium drumming (Project 1), which ended March 1989.

1979 -1989

All thorium workers should have in vivo results, as they were required by the site. However, in the unlikely event that no in vivo results exist for a thorium worker, then coworker intakes will be assigned. The basis for the coworker intakes will be described in Attachment C, *Thorium In Vivo Coworker Study* (in development). Although the actual intake values are in development, the values in the table below are shown as proof of the coworker concept to represent the chronic exposures that thorium workers would have received.

The derived thorium coworker intakes represent the 50th percentile.

1979 -1989 Thorium-232 intakes, (pCi/day)[d]

Period	Type M [b]	GSD[c]	Type S[b]	GSD[c]
1979	13.2	3.60	0.220	7.04
1980-1988	1.01	7.95	0.220	7.04
1989 [a]	1.01	7.95	0.220	7.04

a. Data from 1980 through 1988 are extrapolated to 1989. The thorium processes at Fernald were unchanged between 1988 and 1989.
b. A comparison of absorption type by organ is made and the absorption type resulting in the highest dose is assigned.
c. GSD = Geometric Standard Deviation.
d. These intakes do not represent the finalized values, actual values are in development.

Triple-separated thorium with a ratio of 0.19:1, Th-228:Th-232 is assumed for coworker intakes. For triple-separated thorium, there is no Ra-228 intake associated with the thorium intake.

Thorium workers include: Chemical operators, fork truck drivers, laborers, transportation laborers, operations, production workers and maintenance personnel. Subcontractors from IT Corporation in 1988-1989 should be assumed to be thorium workers unless there is evidence to the contrary. Only one IT claimant has been identified in NIOSH OCAS Claims Tracking System (NOCTS). That individual has in vivo counts showing less than detection Th-232 results near the start and termination of employment. This provides some confidence that IT Corporation workers can be identified and that DOE records can be provided for them.

<u>1990-1994</u>

Thorium workers with no in vivo results, but with pre-job fecal sample results during this employment period at Fernald are recommended to be assigned a dose based on a thorium air concentration of $5x10^{-14}$ µCi/ml (10% DAC), as a maximum potential exposure. The documentation for Project 2 (January 1990 - May 1990) shows the emphasis on air sampling and appeared to be a well-planned and thorough program. Pre-job fecal samples were taken, but not many follow-ups, likely indicating that things went smoothly. The BZ samples must have been filed with the project and never made it into HIS-20, as the earliest thorium samples in the HIS-20 database appear in 1993, with not many until 1995.

With the implementation of DOE Order 5480.11, ambient air monitoring was required in occupied areas with the potential to exceed 10% of any of the DAC values given in Attachment 1 of the order (SRDB Ref ID: 108238, p. 26). The values in Attachment 1 were the same DACs as in the 10 CFR 835 final rule, Appendix A. The access points to any area where airborne radioactive material concentrations exceeded 10% of the DACs in Attachment 1 were required to be clearly and conspicuously posted with a sign that identified the radiological area as an "Airborne Radioactivity Area" (SRDB Ref ID: 108238, p. 31). All radiological areas were required to have an appropriate entry control program to ensure that personnel entry into the radiological areas was controlled (SRDB Ref ID: 108238, p. 31).

Internal dose evaluation programs were required for radiation workers exposed to surface or airborne radioactive contamination where the worker could receive 0.1 rem annual effective dose equivalent from all intakes of all radionuclides from occupational sources, or if any organ or tissue dose equivalent could exceed 5 rem annual dose equivalent (SRDB Ref ID: 108238, p. 26). Note that the monitoring requirement was based on annual dose equivalent instead of committed dose until the implementation of the RadCon Manual in 1992. However, since the determination was prospective, this distinction is not important. Fernald recognized that thorium overpacking operations required internal dose monitoring and evaluation. The implementation of the DOE 5480.11 requirements by January 1990 is readily apparent from the site documentation of the thorium overpacking work (access control, respiratory protection requirements, air monitoring with general area and BZ samples, and pre-job and follow-up fecal samples, if required). This provides confidence that no thorium workers were exposed to greater than 10% of a DAC (respiratory protection being taken into account) on a sustained or average basis.

Since the thorium overpacking procedures did not appear to change much over time, it was considered useful to compare the thorium BZ results from the later periods to the 10% of a DAC assumption proposed for 1990 - 1994. The total annual thorium exposures in DAC-hrs from 1993 - 2006 in the HIS-20 database were fit to a lognormal distribution. The geometric mean of the results without the respiratory protection factor did not exceed 17 DAC-hrs/yr for any of the three data-weighting methods. This is much less than 0.1 DAC times 2000 hrs/yr (200 DAC-hrs/yr) which would be the upper bound. With respiratory protection factors applied, the 95th percentile of the BZ results did not exceed 14 DAC-hrs/yr for any of the three data-weighting methods.

Therefore, the usage of 10% of the thorium DAC limit (5 E-14 µCi/mL) provides a sound basis for this calculation. The thorium dose is based on the assumption of 100% Th-232, as the most claimant-favorable radionuclide. An inhalation and ingestion Th-232 intake is assumed. Although the thorium exposure in 1990 could be limited to January - May (5 months of project 2 work), 2000 hours/year was assumed in this calculation for 1990 - 1994, as a claimant favorable measure. A breathing rate of 1.2 cubic meters per hour was assumed (ICRP 68). The derived inhalation and ingestion intake rates based on 10% of Th-232 DAC are shown in the following table.

Timeframe	Inhalation Rate (dpm/yr)	Ingestion Rate (dpm/yr)
1990-1994	266.4	5.55

dpm = disintegrations per minute

Attachment D provides the detailed calculations used to derive these intake rates. Ingestion doses are assigned as described in *DCAS Technical Information Bulletin, Estimation of Ingestion Intakes*, OCAS-TIB009, where the amount of activity ingested on a daily basis can be approximated assuming it to be 0.2 times the activity per cubic meter of air (SRDB Ref ID: 22397).

<u>1995 and forward</u>

Fernald's HIS-20 database was implemented at the site in the mid-1990s, and is the source of BZ air monitoring data. Some of the data in HIS-20 were migrated from legacy health and safety databases. DOE has also provided data extracted from HIS-20 to NIOSH in the form of Microsoft Access tables. Thorium BZ results begin in 1993 in the HIS-20 database. Beginning in 1995 and later (HIS-20 database), BZ air monitoring data are consistently available. For thorium, the BZ results are isotopic for thorium-228, thorium-230 and thorium-232, although there are few thorium-228 results and these were always analyzed in conjunction with thorium-232. In addition to isotopic thorium results in HIS-20, a review conducted in August 2013 indicated five "custom" nuclides identified as: BL-13, BL-65, CELL 8, KS-65 and RT-210.

Fernald used these "custom" nuclides for known mixtures of nuclides by calculating an effective DAC (EDAC) for the mixture to assign a more accurate DAC-Hr exposure total for BZ air monitoring. The likely definitions for BL-13, BL-65, and KS-65 have been located. These and potential definitions for CELL-8 and RT-210 are described in Attachment E, *Interim Technical Basis for Assigning Doses from Effective DAC (EDAC) BZ Results*. This attachment also provides a method of calculating intakes from the EDAC data for dose reconstruction purposes.

Thorium workers will be assigned thorium doses based on BZ air sampling results. The BZ data will be used to reconstruct thorium intakes, as they are more sensitive than chest counts. If there are no BZ or chest count results after 1995, then no thorium doses are assigned.

Chest count data and BZ air monitoring results may exist for a thorium worker in this timeframe. If all chest count data are negative, then only the BZ air monitoring results are used to evaluate thorium dose. As BZ air monitoring data are considered personal monitoring data and treated no different than other forms of bioassay, missed dose for BZ air monitoring data is included. The current ORAUT-TKBS-0017-5, (Rev 0), *Technical Basis Document for the Fernald Environmental Management Project (FEMP) – Occupational Internal Dose* provides a range of Minimum Detection Levels (MDLs) in Table 5-18. The upper value is used to assess missed dose. Reported values <MDL are set equal to the MDL (corrected for any respiratory protection, to be consistent with the reported measured results). Results are summed and assessed as an annual chronic intake rather than being assessed individually. The solubility class (absorption type) that is in the claimant's records for each radionuclide and year is used for converting reported DAC-hr to activity. The "Max" option (most claimant favorable solubility type) is then selected for material type when entering the results into the Chronic Annual Dose (CAD) workbook.

When evaluating the BZ results, the DAC hours "with respirator" column are used (there are no totals in the "without resp" column). The DAC-hrs for each radionuclide/class combination are summed for each year before inputting the DAC-hr values into the DAC-hr conversion workbook.

However, if thorium BZ air monitoring data are negative, but there are positive chest count results, then chest counts likely would be used to calculate exposures to thorium. In instances when this occurs, an evaluation of the previous in vivo counts is performed to determine if the in vivo results reflect a lung burden that had been previously identified from earlier exposure. If the positive in vivo results are not from an earlier exposure, then they will be used in place of the negative BZA results to evaluate dose.

Additionally, if there are no BZ air monitoring data, but chest counts exist (i.e. from 1979 - 1995), missed thorium dose is calculated based on chest count measurements. This is due to the short-term projects by a few workers where thorium handling due to repackaging deteriorating containers occurred. Unless there is a way to identify when the repackaging efforts occurred and who was involved in them, a missed dose based on chest counts will be done.

Thoron Exposure

Thoron was present at Fernald and a portion released during the processing and storage of the metric tons of a variety of forms of thorium. The primary dose from thoron is to the respiratory tract organs and is delivered primarily by the short-lived daughter products (SRDB Ref ID: 126391). The *Thoron Exposure* paper, Attachment F, provides a basis for recommendations of assigning thoron exposure at Fernald and includes supporting documentation. The table below is taken from Table F-6 of Attachment F.

Thoron Exposure Recommendations

Time Period*	Area/Plant	WLM/year
1977 - 1979	Pilot Plant	0.03
1972 -1989	Storage facilities, repackaging, etc.	1.6
1972 - 2006	Closure Various Storage	0.5

WLM = Working Level Month

*Note that because thoron exposures are associated with thorium exposures, they are not assigned during the thorium SEC periods, (1954-1967 and 1968-1978).

The dates and bounding levels of calculated potential exposures represent recorded operational history. However, thorium was present on site for most of its history. For unknown work locations and time periods of concern, Dose Reconstructors should assume that thoron exposure potential existed, as a claimant favorable assumption, and assign thoron doses based on the guidance from the table. Assumptions based on work history related to the time periods and "operational" assignments can be made to provide bounding assessments.

Example Dose Reconstructions

Attachment G provides example dose reconstructions performed on 4 cancers under multiple scenarios to demonstrate direct application of the methods presented in this paper. The cancers selected for the purposes of illustration were the lung, bone, prostate and skin.

Conclusion

This white paper provides a methodology for the assignment of thorium and thoron doses at Fernald during the post SEC period, 1979 - 2006. The assessments presented in this white paper define the methods by which a dose estimate can be determined for Fernald thorium and thoron workers. These methods support NIOSH's conclusion that the operationally-related internal thorium and thoron dose can be bounded.

References

ORAUT (Oak Ridge Associated Universities Team), 2014, *Guiding Reconstruction of Intakes of Thorium Resulting from Nuclear Weapons Programs*, ORAUT-OTIB-0076 Rev 00-A, Oak Ridge, Tennessee, DRAFT.

Attachments

A. Post production Thorium Activities Timeline by Gene Potter

B. Methods for estimating intakes for thorium from chest counts are given in the supporting papers authored by Tom LaBone.

1. Evaluation of Fernald Ac-228/Pb-212 Chest Count Data, 04/18/2013,
2. Activity Ratios for various types of Thorium, 06/21/2013,
3. Approximate Evaluation of Pb-212 Chests Counts Following Intakes of Thorium, 07/19/2013,
4. Using Ac-228 and Pb-212 to Measure Intakes of Th-232, 09/18/2013.

C. Thorium In Vivo Coworker (in development).

D. Calculation for assigning thorium inhalation and ingestion doses based on 10% of a Th-232 DAC by Karen Kent.

E. A Technical Basis for Assigning Doses from Effective Derived Air Concentration (EDAC) Breathing Zone Air (BZA) Sampling Results by Gene Potter.

F. Thoron Exposure Paper by Bryce Rich.

G. Fernald Example Dose Reconstructions by Karen Kent.

ATTACHMENT A

FEMP Post-Production Thorium Activities

Year	Description	References
1979	Thorium processing ended.	

<table>
<tr><td rowspan="2">1985</td><td>“On March 2, 1985, six breathing zone air samples were collected on three Plant 1 employees, who were transferring thorium residues from corroded drums into new drums. During this operation north of Building 65, all employees wore air-purifying half-mask respirators equipped with purple radionuclide filter cartridges.” (p. 2). Contains the six results that are in the “Fernald Thorium Air Final” database and the “AIRSAMP_thorium” workbook.</td><td>34321</td></tr>
<tr><td>July 15, 1985 Letter from NLO to DOE. “Over 2,000 tons of thorium compounds, containing approximately 1,100 tons of elemental thorium, are presently stored at the FMPC. Most of this material is stored in steel 55-gallon drums, some of which have begun to show serious deterioration due to corrosion ... It is necessary that these thorium compounds be repackaged without much delay. If repackaging is not done soon, some of the drums may collapse and spill their contents onto the floor of the warehouse where they are stored. That spillage would result in a serious health hazard” (p. 2).</td><td>88205</td></tr>
<tr><td rowspan="3">1986</td><td>When WMCO took over the contract in January 1986, it “aggressively” upgraded the air sampling program, provided written procedures, and planned to introduce breathing zone sampling for all non-routine functions.</td><td>4152</td></tr>
<tr><td>Report of a task force “assembled to investigate possible overstressed conditions in the silo and bins used to store thorium oxide in Plant 8. This investigation was initiated based on a May 9, 1986 report by Lockwood Greene which stated that overstressed conditions and possible failure could occur during a seismic event or high winds” (p. 7). Considers the options for dealing with the problem.</td><td>28862</td></tr>
<tr><td>Shows completed actions on Plant 8 Silo Structural Remediation June 1986-September 1986 (p. 7).</td><td>29071</td></tr>
<tr><td rowspan="2">1987</td><td>An environmental assessment identified 212 drums containing 241 smaller containers on thorium materials stored outside of Building 65 and more than 13,000 containers presently stored in FMPC warehouse buildings #64, 65, 67, and 68. An estimated 175 metric tons of thorium material was in the Plant 8 bin and silo storage; it was estimated that approximately 2,500 205-liter drums or 400 double-walled boxes would be generated during removal of this material.</td><td>4611</td></tr>
<tr><td>Results of surveys taken in the thorium warehouse buildings, 64, 65, 67, and 68 in October (p. 11).
<table>
<tr><th>Building</th><th>Average Airborne Reading</th><th>Maximum Airborne Reading</th></tr>
<tr><td>64</td><td>0.00270 W.L.</td><td>0.00541 W.L.</td></tr>
<tr><td>65</td><td>0.41700 W.L.</td><td>0.74300 W.L.</td></tr>
<tr><td>67</td><td>0.01550 W.L.</td><td>0.02700 W.L.</td></tr>
<tr><td>68</td><td>0.65000 W.L.</td><td>0.75000 W.L.</td></tr>
</table></td><td>44271</td></tr>
</table>

	From a thorium handling environmental assessment for removal of the material from the Plant 8 silo and bins (aka Project 1): "Exposure to airborne and surface contamination will be minimized by personal protective equipment (PPE), routine monitoring, and operational procedures. Personnel exposure will be controlled to levels which meet DOE requirements or ALARA objectives. … Air samples will be collected during repackaging operations to document that personnel exposures are acceptable. Airborne thorium concentrations within working area will not be allowed to exceed 0.02 becquerels alpha activity per cubic meter averaged over a 40-hour work week (WMCO, 1986), the Derived Air Concentration for Th-232 (ICRP, 1979b)." (p. 22). This is the Class W DAC for Th-232. One of the references in the assessment was the draft DOE order that became 5480.11. This seems to indicate that the DACs were in use even before DOE 5480.11 implementation.	29077 26093 is another version
1988	FMPC Facility Profile June 17, 1988 indicated major environmental problems areas included "20,672 drum equivalents of thorium stored on site" (p. 5).	40307
	In 1988, Fernald initiated a "three Project plan" for improving the temporary storage conditions for thorium (p. 203; see also Ref ID 84457).	3559
	The first project work was subcontracted to IT Corp.	33877
	"The first project addresses the bulk thorium materials in the Plant 8 silo and bins. In September 1987, the FMPC began the design and construction of the handling system necessary to remove and package the bulk thorium materials. Following construction, the removing, handling, and packaging of thorium began in November 1988." (p. 451)	3554
1989	Implementation of DOE Order 5480.11 on 1/1/1989. "The requirements of the revised Order are, in many cases, new or more stringent than those previously established. It is recognized that the contractor may not be in full compliance with all the requirements of DOE 5480.11 as of the effective date" (p. 5). The sites were required to submit a status report to DOE by January 27, 1989 with requests for exemptions and an implementation plan detailing how compliance will be achieved by December 31, 1989 (i.e., full compliance was not required until December 31, 1989 unless the implementation plan specified an earlier date). There are implementation plans for several other sites listed in the SRDB. This Order superseded DOE 5480.1A, Environmental Protection, Safety, and Health Protection Program for DOE Operations, of 8-13-81, Chapter XI, "Requirements for Radiation Protection" (p. 10). The DACs for Th-232 in 5480.11 were the same as those listed in 10CFR835 final rule, namely 5E-13 µCi/ml Class W and 1E-12 µCi/ml Class Y (p. 63)	108238, pp. 5-82
	"Prior to February 1989, no isotopic analysis for plutonium,	33900

	neptunium, or thorium isotopes had been performed for smears or air sampling filters" (p. 7).	
	Discussion in the review of an incident in February 1989 during Project 1: "High volume and BZ (breathing zone) air sampling has been extensively performed. Instances where long lived airborne radioactivity was found above the 1.5 x 10^{-12} µCi/ml or 1 working level were examined as to the adequacy of respiratory protection provided during those periods. Respiratory protection prescribed for various operations consists of full face respirator for thorium repackaging and airline respirator for thorium storage containments. A full face respirator is required for work in any area having removable alpha surface contamination above 500 dpm/I00 cm^2 until air sampling shows no significant airborne radioactivity. The review showed that for each instance where elevated airborne levels were measured, the protection factor provided by the prescribed respirator was adequate for personnel protection" (p. 6).	33877
	Project 1 completion: "As the bulk materials were removed from the silo and bins, they were placed in double containment drums called overpacks (a 48-gallon drum is packaged inside a 55-gallon drum), inventoried and monitored. The drums were then stored in a new onsite warehouse. This project was completed in March 1989. The silo and bins are to be decontaminated and demolished." (p. 451)	3554
	Training for Project 2 was not conducted until August-December 1989.	44282
	FSAR for Project 2 published in September 1989. The document contains a complete description of anticipated operations and protective measures to be employed. Airline respirators were to be worn by the overpacking operator and laborer, and HEPA filtered ventilation system was provided for the forktruck driver (p. 18). Access to the building was restricted during overpacking operations. One operator was to wear a BZ sampler outside of the protective clothing and a BZ sampler was to be in the forktruck. At least one radiation technician and health physicist were required to be on-site during overpacking. (p. 57-58)	4188
	Thorium repackaging project air sample counting procedure, November 1989: "The minimum activity which the system is required to detect (MDA) is the 10% DAC standard, though we feel that the system will detect less activity."	33954
	SOP issued December (applicable to Project 2): "At least one operator involved in repacking shall wear a breathing zone lapel sampling monitor. Other personnel may be requested to wear monitoring equipment during the operation" (6.22). "Any circumstance which could result in an intake of radioactive materials by inhalation, ingestion or absorption, shall immediately be reported to a supervisor. The supervisor shall immediately report the circumstance of possible radioactive materials intake to	44281

	Radiological Safety and or Dosimetry for evaluation. Radiological Safety in conjunction with Dosimetry will decide upon the appropriate course of action for evaluating the potential intake. NOTE: Operators, Radiological Safety Technicians (RST) and Material Control and Accountability (MC&A) personnel shall submit a background fecal sample prior to starting operations" (6.37)	
	1989 environmental report says "all thorium stored outside in drums is now stored indoors." (p. 23). However, this does not appear to have happened until May 1990 (see below).	3555
1990	Thorium inventory dated January (start of Project 2): 15,000 drums stored in warehouses. 212 drums stored on an outside pad. Outside storage tank contained 19,585 lbs of thorium solution. (p. 2)	83668
	From a summary of radiological controls used in the thorium repackaging project in February (Project 2). Among the "health physics controls" was "Each thorium operator is required to wear a Breathing Zone (BZ) sampler at all times while he is inside the Radiological barrier fence." (p. 3)	33882
	From an SOP in March that would have applied to project 2 and later: "Before, at three month intervals during and at completion of the job, individuals working with thorium shall have in vivo lung measurements performed. Individuals whose work includes routine handling of thorium shall be required to submit background fecal samples prior to initiating work." (6.3.1). "Air sample results indicating a thorium inhalation in excess of 8 DAC hours (with the respiratory protection factor considered) shall trigger in vivo measurement and/or bioassay." (6.3.2). "At least one operator involved in the repackaging of the thorium shall be required to wear a BZ sampler." (6.5.4). "Radon-220 working level samples shall be taken at least twice per shift" (6.5.5)	33913
	Environmental Restoration and Waste Management monthly progress report for May: Actual work on Project 2 was January-May 1990. "Thorium Overpacking. One hundred seventy-five drums of thorium had been overpacked as of April 30, 1990. Temperature restrictions and equipment malfunctions have hampered progress. Completion of Thorium Overpacking is expected in early May 1990." (p. 14)	33893
	Press release in May: "The second of two projects to alleviate environmental and safety concerns stemming from the storage of thorium materials at the U, S. Department of Energy's Feed Materials Production Center has been successfully completed." (p. 2)	44304
	Change to OSR in May: "The proposed change would be to remove the pressure relief valves from the 85-gallon drum lids used to maintain Argon gas at 2 psi. in drums used for long term storage of materials designated suspect pyrophoric. These relief valves would be replaced with equivalent rupture discs."	44303

	Internal Dosimetry Technical Basis Manual, issued in December, "Thorium is stored on-site in approximately 15,000 containers of various sizes ... There are no routine ongoing operations that involve the processing or handling of thorium. The major potential source of exposure to thorium material at the FMPC is the repackaging of thorium drums. This operation is covered under the IRS&T Safety Procedure, SP-P-35-014, 'Radiological Controls for Repackaging Thorium'" (p. 47). "All compounds of thorium at the FMPC are assigned to inhalation class Y" (p. 48).	4145
1991	In Vitro Bioassay Requirements for the WMCO Feed Materials Production Center, April: Operational monitoring requirement specific to overpack project: "For the Thorium overpack project, isotopic fecal sampling is the only method capable of monitoring intakes below the Annual Limit on Intake. It is anticipated that about 50 fecal samples will be obtained for this project over the next year. These samples will require alpha spectrometric analysis for Th-232, Th-230 and Th-228 with a detection limit of 1.0 dpm/sample."	34636
	Annual Environmental Report for 1991 covers the start of Project 3: 1991-end of 1993 (planned), "overpacking 13,000 containers of thorium, was begun in 1991. Overpacking in the Thorium Warehouse was completed; overpacking in the Plant 1 Thorium Warehouse and the Pilot Plant Warehouse are scheduled for completion by September 1992. The FEMP has proposed to complete the overpacking in the (Old) Plant 5 Warehouse by the end of 1993." (p. 203) "In June 1991, approximately 1,094 metric tons (1,190 tons) of thorium were declared waste. Once this affirmation occurs, the FEMP prepares to move the thorium offsite. In September 1991, nearly 150 metric tons (160 tons) were sold to a commercial vendor. … The majority of the thorium materials, about 13,300 containers (containers vary in size from 55-gallon drums to drums as small as one gallon), is stored in the Thorium Warehouse, the (Old) Plant 5 Warehouse, the Plant 1 Thorium Warehouse, and the Pilot Plant Warehouse (Figure 53). About 9 metric tons (9.9 tons) of thorium nitrate solution are stored in Pilot Plant Tank 2. The remaining thorium material consists of about 175 metric tons (190 tons) of bulk thorium oxide, plus inert materials like an absorptive, silica-rich deposit which had been contained in the Plant 8 silo and bins prior to their dismantling in 1989. This material is now safely packaged in new, double containers and is stored in Building 60." (pp. 202-203) "On July 28, 1991, the FEMP completed the overpacking of and relocation of 35 thorium containers characterized as mixed waste to a RCRA warehouse. Also completed were the necessary overpacking, relocation, and RCRA evaluation actions for all but 16 of 192 containers which require further characterization … The	3559

	characterization of the 16 remaining containers is scheduled to be complete in June 1992." (p. 90-91)	
1992	"During 1992, ... for the first time, the site shipped thorium wastes to NTS. The Fernald site continued work on the final stage of a three-project plan to improve the temporary storage conditions for the onsite thorium inventory" (p. 18). "Between January 1, 1992, and April 1, 1993, more than 1,600 drums of thorium materials were shipped to NTS. The characterization of the last 16 containers required to be further characterized in accordance with the SACD was completed in June 1992" (p. 79). "As part of the third project, overpacking in the Pilot Plant Warehouse was completed in 1992. Site personnel also conducted overpacking activities in the Plant 1 Thorium Warehouse, and these activities are expected to be completed in 1993. Overpacking activities are not yet complete in the (Old) Plant 5 Warehouse. Until the Fernald site can provide final disposition of the thorium waste, safe storage will be required. During 1992, some of the thorium was repackaged and transferred to the (Old) Plant 5 Warehouse" (pp. 178).	3563
1993	"In 1993, three drums of thorium materials were shipped to the Nevada Test Site. Also in 1993, the site completed the overpacking of 6,100 drums of thorium materials and expects to have approval to ship those materials to Nevada in 1994" (p. 81).	3569
1994	"In 1994, the Fernald site shipped 750.4 drum equivalents of thorium material to the DOE Nevada Test Site (NTS) for disposal. Additional shipments are planned for 1995" (p. 91).	3575
1995	Building 65 Thorium Overpack Project (TOP) Project to overpack 5,600 drums into White Metal Boxes or Thorium Overpack Containers and stage for shipment to NTS was anticipated to begin in November 1995, but did not start until 1996 (see below).	130104
	"Almost 6,000 gallons of thorium nitrate, a contaminated acid waste stream, were treated and solidified safely in 1995 … The final rinse of the thorium nitrate tank was completed November 9, 1995, less than two months after Chem-Nuclear, FERMCO's subcontractor, began processing the material." (p. 41). In 1995, the Fernald site shipped 776 drum equivalents of thorium material to the NTS for disposal. Additional shipments are planned for 1996 (p. 104).	3578
1996	Start of TOP, May 1996 (p. 26). "Safe shutdown activities in the Plant 9/Thorium Complex have been completed" (p. 90). "In 1996, the FEMP shipped 2,112 drum equivalents or 46,101 cubic feet of thorium material to the DOE (NTS) for disposal" (p. 93).	3586
1997	"In 1997, the FEMP removed 3,400 containers of thorium material and shipped 10,875 drum equivalents, or 80,480 cubic feet (2,279 m^3), of thorium material to the Nevada Test Site for disposal, completing the Thorium Overpack Project. Characterization of the remaining estimated 8,500 containers of thorium legacy waste at the FEMP was initiated in 1997" (p. 54).	3592
1998	The characterization documentation and formal RCRA waste	3604

	determinations for the remaining estimated 8,500 containers of thorium legacy waste continued in 1998" (p. 51).	
1999	"Thorium/Plant 9 Complex decontamination and dismantlement was completed. The subcontractor completed field work in February, including structural steel size reduction, decontamination, and demobilization. The project closeout report was submitted to the regulatory agencies and approved in April" (p. 47). The characterization documentation and formal RCRA waste determinations for the remaining estimated 8,500 containers of thorium legacy waste continued in 1999" (p. 52).	3606
	"The characterization documentation and formal RCRA waste determinations for the remaining estimated 8,500 containers of thorium legacy waste resumed in 1999" (p. 47).	129791
2000	The characterization documentation and formal RCRA waste determinations for the remaining estimated 8,500 containers of thorium legacy waste continued in 1999. In 2000 over 6,000 of these containers were shipped to Nevada Test Site for disposal" (p. 47).	9010
2001	The characterization documentation and formal RCRA waste determinations for the remaining estimated 8,500 containers of thorium legacy waste were continued in 1999. Through the end of 2001, over 6,400 of these containers were shipped to Nevada Test Site for disposal. This shipping effort removed over 1,000,000 pounds (454,000 kg) of thorium from the total site thorium inventory" (p. 44).	3516
2002	The characterization documentation and formal RCRA waste determinations for the remaining estimated 8,500 containers of thorium legacy waste resumed continued in 1999. Through the end of 2002, over 7,100 of these containers were shipped to Nevada Test Site for disposal. This shipping effort removed over 1,250,000 pounds (568,000 kg) of thorium from the total site thorium inventory" (p. 51).	126955
2003	"Through the end of 2003, over 8,400 of these containers were shipped off-site for treatment, with subsequent disposal at the Nevada Test Site. Those containers sent off-site for treatment and subsequent disposal included all RCRA hazardous thorium legacy-waste that had a scheduled milestone of December 5, 2003. This shipping effort removed approximately 1,500,000 pounds (681,000 kg) of thorium from the total site thorium inventory. The remaining thorium inventory of approximately 100 containers has been evaluated. Of this remaining inventory, approximately 90 containers are non-RCRA, low-level radioactive waste and 10 are RCRA hazardous waste" (p. 51).	126956
2004	The thorium waste determined to be hazardous under RCRA and requiring off-site treatment will be prepared and shipped by September 30, 2004 for treatment to meet land disposal restrictions. The RCRA hazardous thorium inventory amenable to	126956

	treatment on-site will be dispositioned by June 30, 2004" (p. 51).	
	"In 2004, the FCP shipped 4,274 pounds (1,940 kg) of mixed thorium waste to Envirocare of Utah, Inc. for treatment and disposal, and 21,192 pounds (9,621 kg) of non-hazardous thorium waste to the Nevada Test Site for disposal. At the end of 2004, there were only a few containers of thorium waste remaining on site" (p. 45).	129790
2005	"In 2005, the FCP shipped 1,051 pounds (477 kg) of mixed thorium-contaminated oil to Envirocare of Utah, Inc. for treatment and disposal. At the end of2005, there were only three containers of thorium-contaminated mixed waste remaining on-site. These containers are planned for shipment to Envirocare of Utah, Inc. in early 2006" (p. 48).	129791
2006	"With the completion of remediation, DOE also completed the disposition of the containerized waste inventory. The last shipment of hazardous waste occurred October 2, 2006, ending hazardous waste management activities" (p. 57). 10/29/2006 – remediation was complete (p. 20). "The DOE's Office of Legacy Management and their Technical Assistance Contractor, S.M. Stoller Corporation, assumed full responsibility for operations at the Fernald site on November 17, 2006" (p. 15).	129793

ATTACHMENT B-1

Evaluation of Fernald Ac-228/Pb-212 Chest Count Data

Tom LaBone
April 18, 2013

Summary

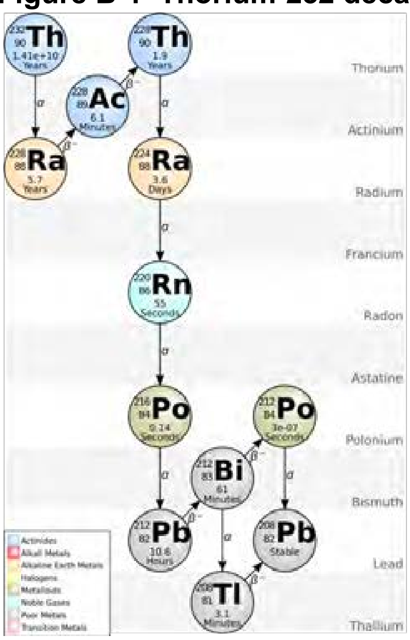
In a previous white paper we presented a method for estimating Th-232/Th-228 intakes using Pb-212 chest count results. SC&A was in general agreement with this method but expressed concerns about the relative amounts of Ac-228 and Pb-212 measured in some

chest counts. Here, we show that after adjusting for bias in the chest counts the amounts of Ac-228 and Pb-212 present are usually consistent with the model we are using to evaluate the data. In the rare occasions when the amounts of Ac-228 present are inconsistent with this model, we recommend that the excess Ac-228 be interpreted as being the result of intakes of unsupported Ra-228.

Introduction

The white paper *Calculation of Chronic Intake IRFs for Th-232 Assuming Shared Kinetics*[1] discusses how measured Pb-212 chest burdens will be interpreted in terms of Th-232/Th-228 intakes. The interpretation of Ac-228 chest burdens was not addressed in that report because, unlike the Pb-212, the amount of Ac-228 present in the chest may not be closely related to the amount of Th-232/Th-228 present. This is because the Ra-228 parent of Ac-228 can exist in significant quantities in the workplace independent of Th-232 because of its relatively long half-life (as shown in the decay scheme below).

Figure B-1 Thorium-232 decay chain (from *Wikipedia*)



SC&A basically agreed with this conclusion in a white paper[2] issued in 2012, but raised additional concerns about the chest count data:

[1] Rev. 00, issued February 17, 2012. Authored by Tom LaBone.
[2] Joyce Lipsztein and Bob Barton *COMPLETENESS AND ADEQUACY OF THORIUM IN-VIVO RECORDS (1979–1989)* S. Cohen & Associates, November 2012.

For the period 1979–1988, NIOSH has proposed to use the Pb-212 results and discard the Ac-228 results, as the Pb-212 results are considered more reliable. SC&A agrees that this is a correct statement, because the equilibrium status (relative proportion of Th-232 to Ac-228 and Pb-212) of the source is not known. On the other hand, most of the results above the MDA have higher activity results for Ac-228 than for Pb-212. Many times, Ac-228 results were higher than the MDA, but Pb-212 results were below the MDA. NIOSH has not provided an explanation for this phenomenon.

In this report the Ac-228/Pb-212 ratios of the chest count data will be examined in an effort to address these concerns.

Manipulation of Fernald Chest Count Data

The Ac-228 and Pb-212 results from chest counts performed at Fernald from 1978 to 1988 were analyzed separately by year. Based on previous experience, the distributional model for these annual data is that they are a combination of a normal analytical background distribution with a mean of zero and a lognormal exposure distribution [see RPRT-44]. The normal component of the data is estimated by fitting a line through the negative data on a normal probability plot. The intercept of the line is the estimate of the mean/median of the normal distribution and the slope is the estimate of the standard deviation. If the median of the distribution is not equal to zero the data are assumed to be biased. For example, the normal probability plot for the Pb-212 chest count data from 1978 are shown below in Figure B-1. The median of the data is -0.019 nCi, which means that the data are assumed to be biased by that much. The data are adjusted for any bias and then refit in order to force the line through zero (i.e., make the median equal to zero). For example, the adjusted 1978 Pb-212 data are shown below in Figure B- 2.

Figure B-2 Normal probability plot of Pb-212 chest count results for 1978. The line is a robust regression of the data that are less than zero nCi.

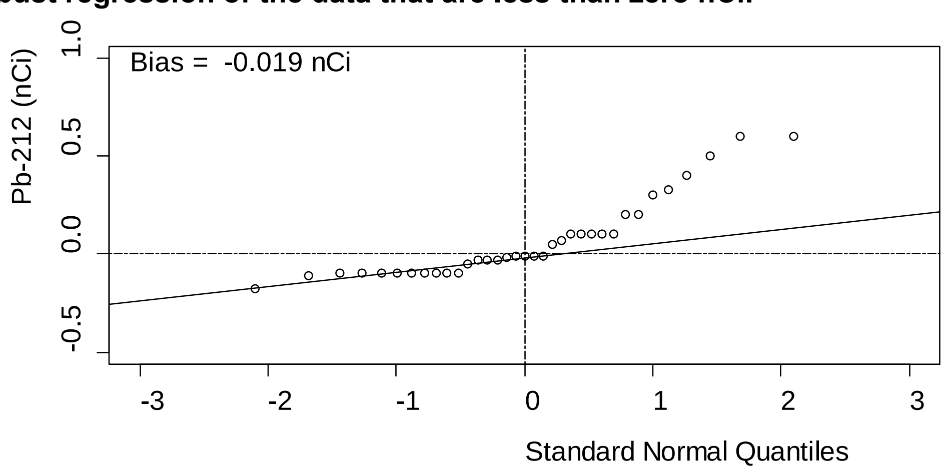
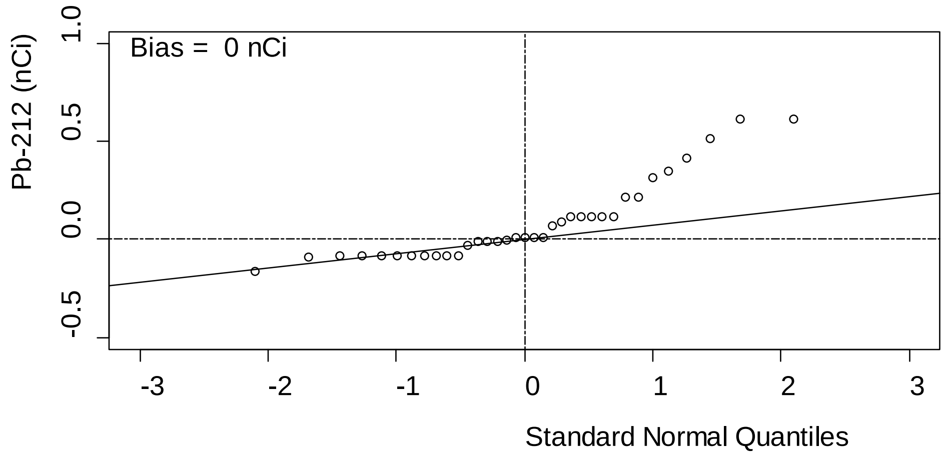
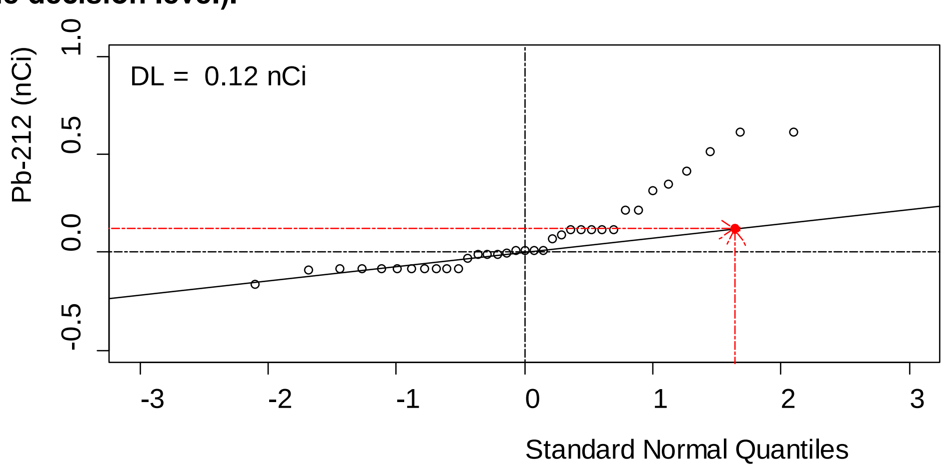


Figure B-3. Normal probability plot of Pb-212 chest count results for 1978 after adjusting for bias. The line is a robust regression of the data that are less than zero nCi.



The process decision level (DL) above which a measured chest burden is deemed to be "positive" is taken to be the 95th percentile of the (unbiased) normally distributed analytical background. For the 1978 Pb-212 data, the DL is 0.12 nCi as shown in Figure B-3. Measured Pb-212 chest burdens below this DL are deemed to not indicate the presence of Pb-212.

Figure B-4. Normal probability plot of Pb-212 chest count results for 1978 after adjusting for bias. The line is a robust regression of the data that are less than zero nCi, and the red point is the 95th percentile of the background normal distribution (i.e., the decision level).



A summary of the bias and DL for Ac-228 and Pb-212 for years 1978 through 1988 are given in Table B-1 below and the corresponding plots are given in Appendix A. The DL's for Pb-212 ranged from 0.11 to 0.18 with a mean of 0.13 whereas the DL's for Ac-228 ranged from 0.08 to 0.17 with a mean of 0.11. For simplicity, a single DL of 0.12 nCi will be adopted for both nuclides for all years. If a minimum detectable amount (MDA) is need for dose reconstruction purposes, a value of 2□DL = 0.24 nCi should be used for both nuclides.

Table B-1. Summary of bias and DL for Ac-228 and Pb-212 for each year.

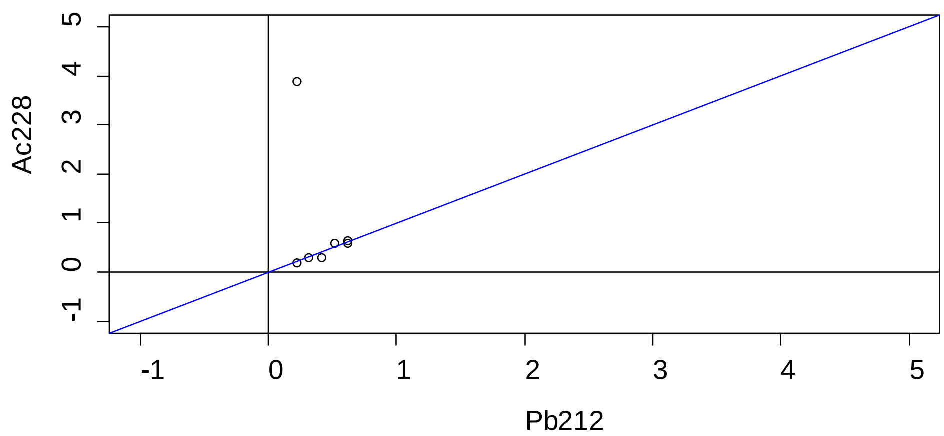
Year	Pb-212 Bias (nCi)	Pb-212 DL (nCi)	Ac-228 Bias (nCi)	Ac-228 DL (nCi)
1978	-0.019	0.120	0.008	0.153
1979	-0.014	0.156	0.031	0.169
1980	-0.045	0.123	0.025	0.091
1981	-0.056	0.108	0.022	0.127
1982	-0.058	0.121	0.010	0.117
1983	-0.101	0.122	-0.008	0.097
1984	-0.089	0.111	0.001	0.079
1985	-0.086	0.117	0.017	0.102
1986	-0.085	0.128	0.020	0.114
1987	-0.047	0.123	0.008	0.106
1988	0.002	0.181	0.058	0.107

Discussion of Ac-228 and Pb-212 in Chest Counts

In Figure B-4, chest burdens from 1978, where both Ac-228 and Pb-212 are greater than the DL, are presented (Ac-228/Pb-212 plots for all years are presented in Appendix B). These data are considered to be above the level of analytical noise and represent actual material in the chest[3]. The diagonal blue line has a slope of 1 and an intercept of 0. Data falling exactly on this line have equal quantities of Ac-228 and Pb-212. All of these measurement, except for one, are considered to indicate equal quantities of Ac-228 and Pb-212 in the chest (to within measurement uncertainty).

[3] If one looks at the Ac-228 to Pb-212 ratio and includes results that are basically noise, one can expect to see quite a range of ratios beyond the anticipated 1:1 that will be very difficult to interpret in a meaningful way.

Figure B-5. Plot of Ac-228 versus Pb-212 for 1978 where the levels of both nuclides are above the decision level. The blue line has a slope of 1 and an intercept of 0.



The lone outlier has an Ac-228/Pb-212 ratio of ~18. The only plausible explanation for such a large ratio is the presence of unsupported Ra-228. This suggests that the Ac-228 activity in excess of the Pb-212 activity should be interpreted as a Ra-228 intake and assessed separately from the Th-232/Th-228 intake estimated from the Pb-212. Acute and chronic intakes of Ra-228 measured with Ac-228 are readily evaluated with IMBA and do not require custom treatment.

Appendix A

Two plots are given for each year. The first is a normal probability plot of the Pb-212 data. The median of the Pb-212 data was estimated from a robust regression to the negative (less than zero) data. The median, which is identified as the "bias" on the plot, was then subtracted from each result. The data on the plot are bias-corrected. The regression was repeated on the bias-corrected data to obtain the standard deviation and mean of the normal background distribution. These parameters were then used to calculate the decision level (DL), which is assigned the 95th percentile of the normal background data. The second plot is the same as the first except it is for Ac-228.

Appendix B

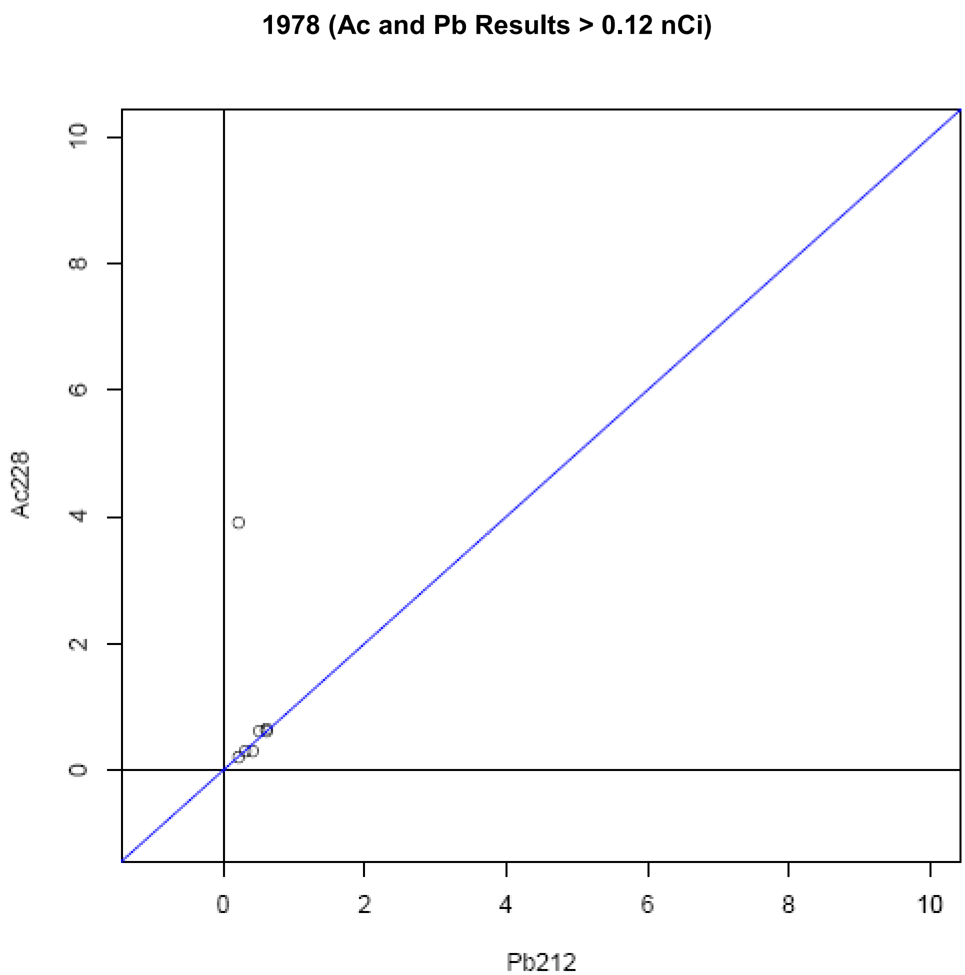
For each year four plots of Ac-228 versus Pb-212 are given:

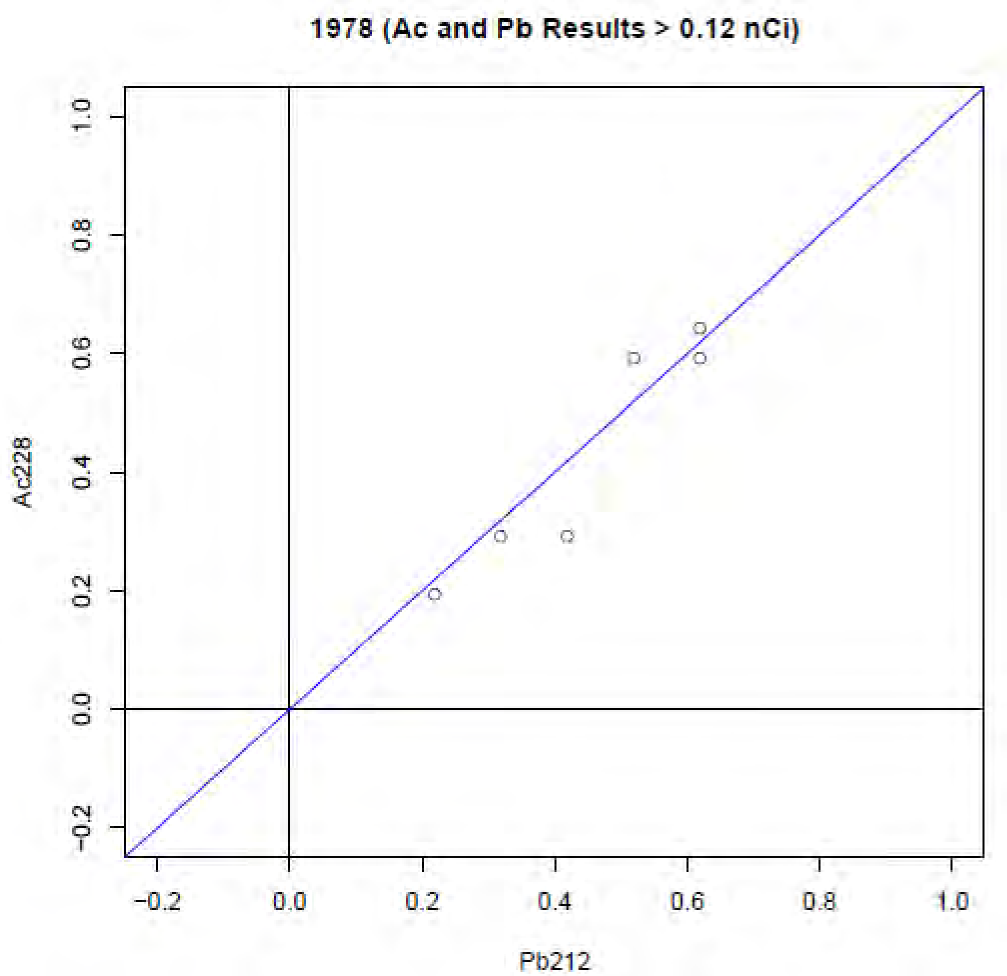
The first plot is the Ac-228 versus the Pb-212 where both nuclides are above the DL.

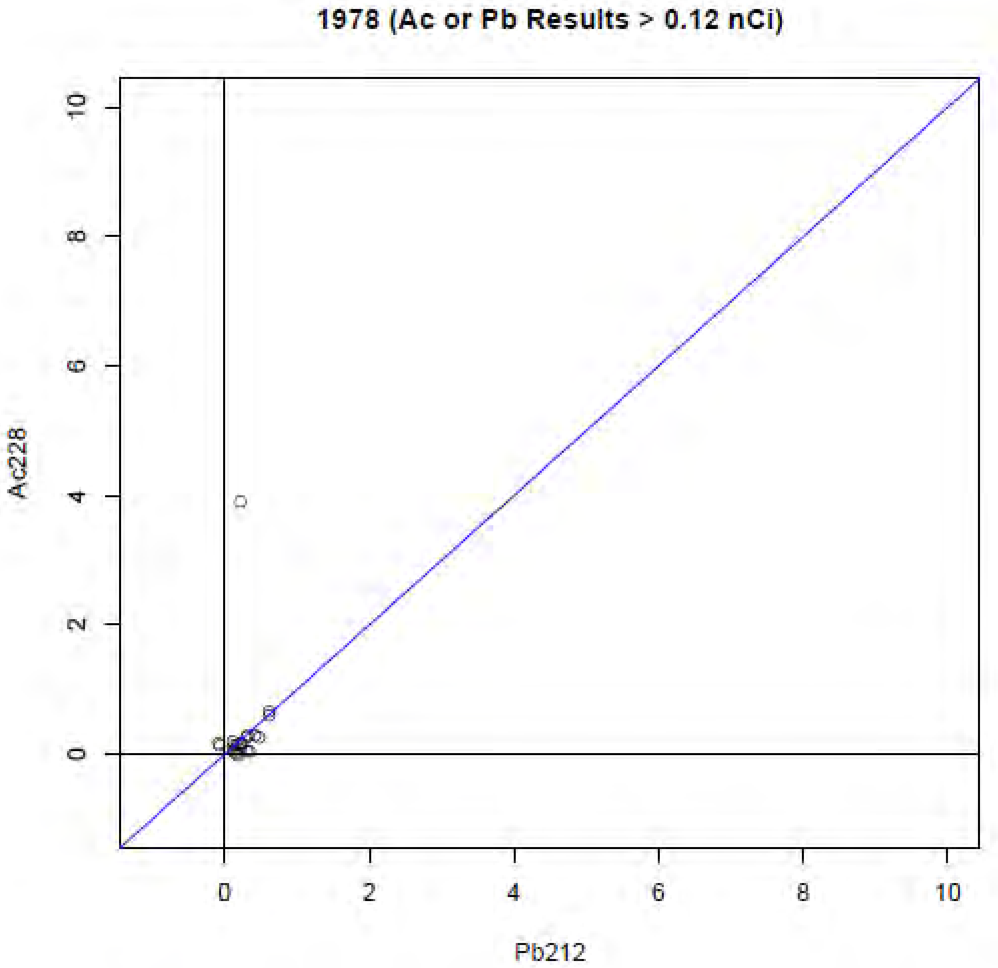
The second plot is the same data as the first plot but with a different scale on the X and Y axes.

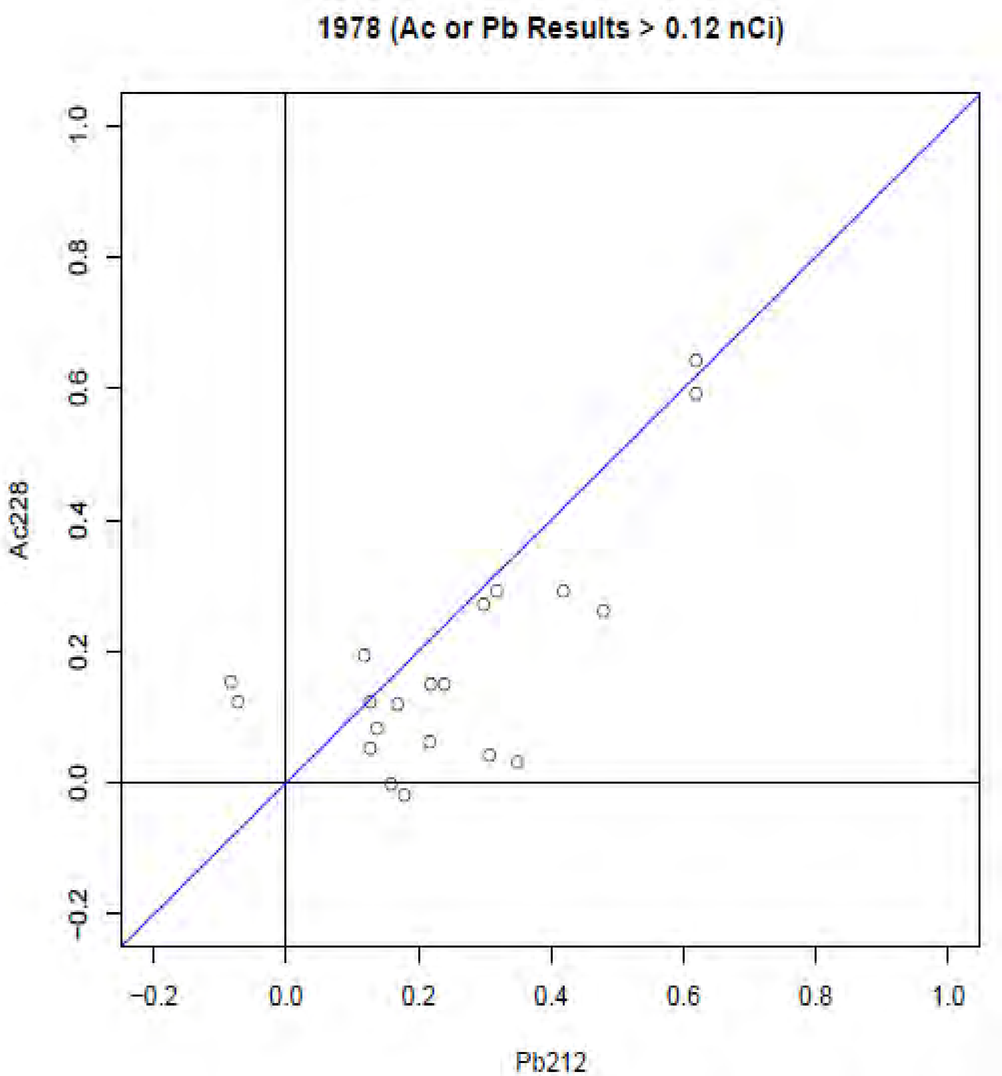
The third plot is the Ac-228 versus the Pb-212 where either nuclide is above the DL.

The fourth plot is the same data as the first plot but with a different scale on the X and Y axes.




1978 (Ac and Pb Results > 0.12 nCi)
Ac228
Pb212
-0.2
0.0
0.2
0.4
0.6
0.8
1.0


1978 (Ac or Pb Results > 0.12 nCi)
Ac228
Pb212
0
2
4
6
8
10


1978 (Ac or Pb Results > 0.12 nCi)
Ac228
Pb212
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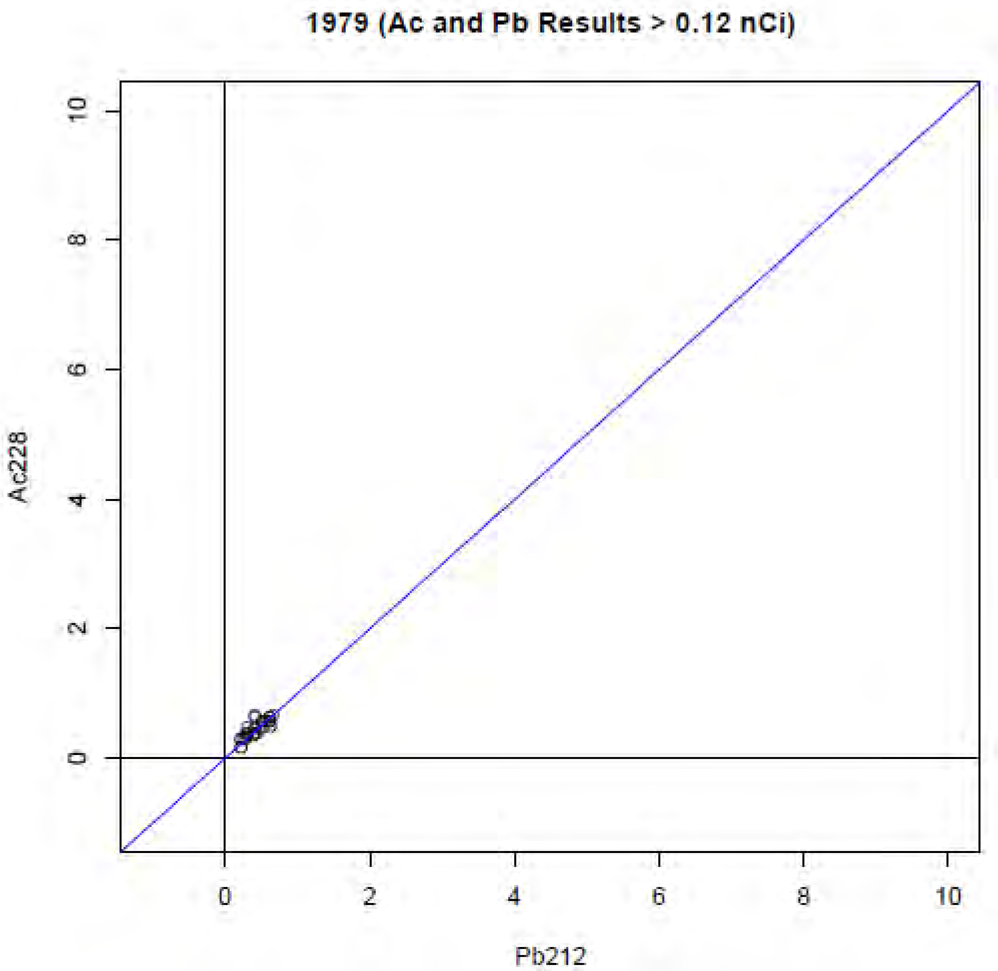
0.0
0.2
0.4
0.6
0.8
1.0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Ac228
Pb212
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4
6
8
10
0
2
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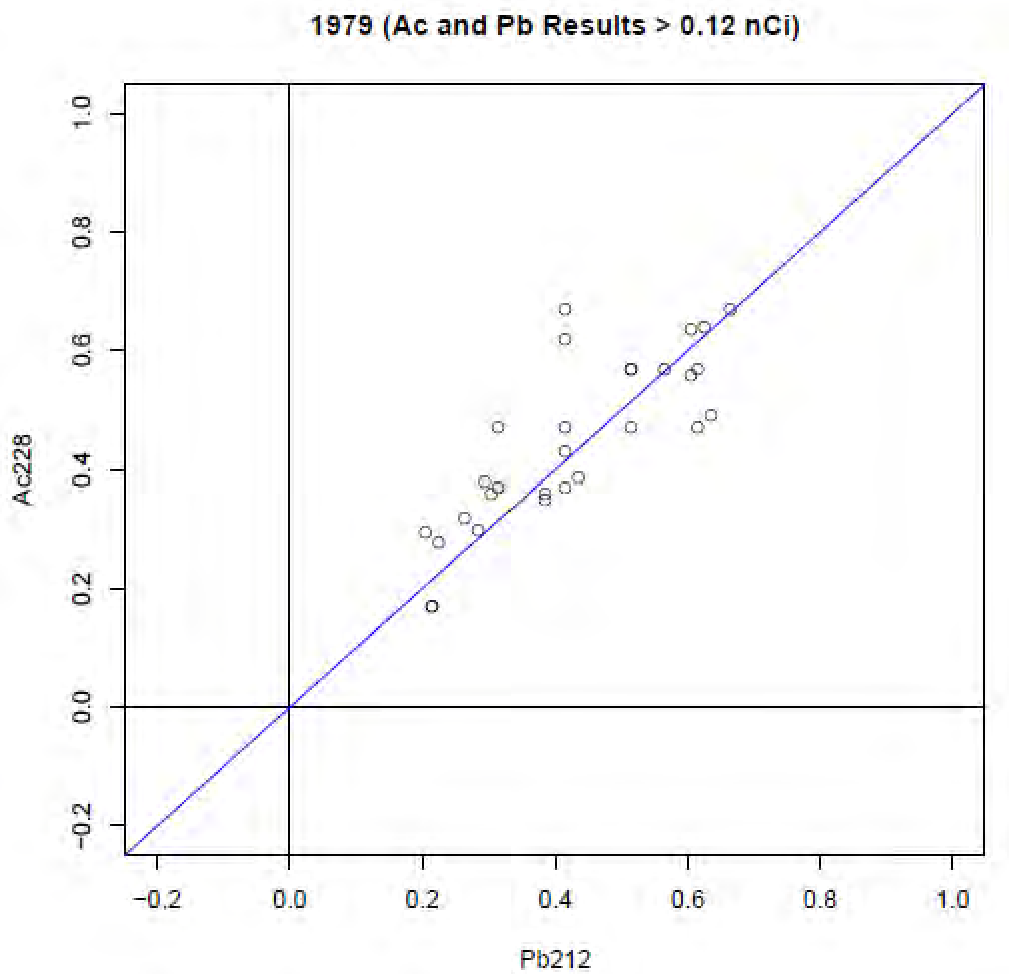
10


1979 (Ac and Pb Results > 0.12 nCi)
Ac228
Pb212
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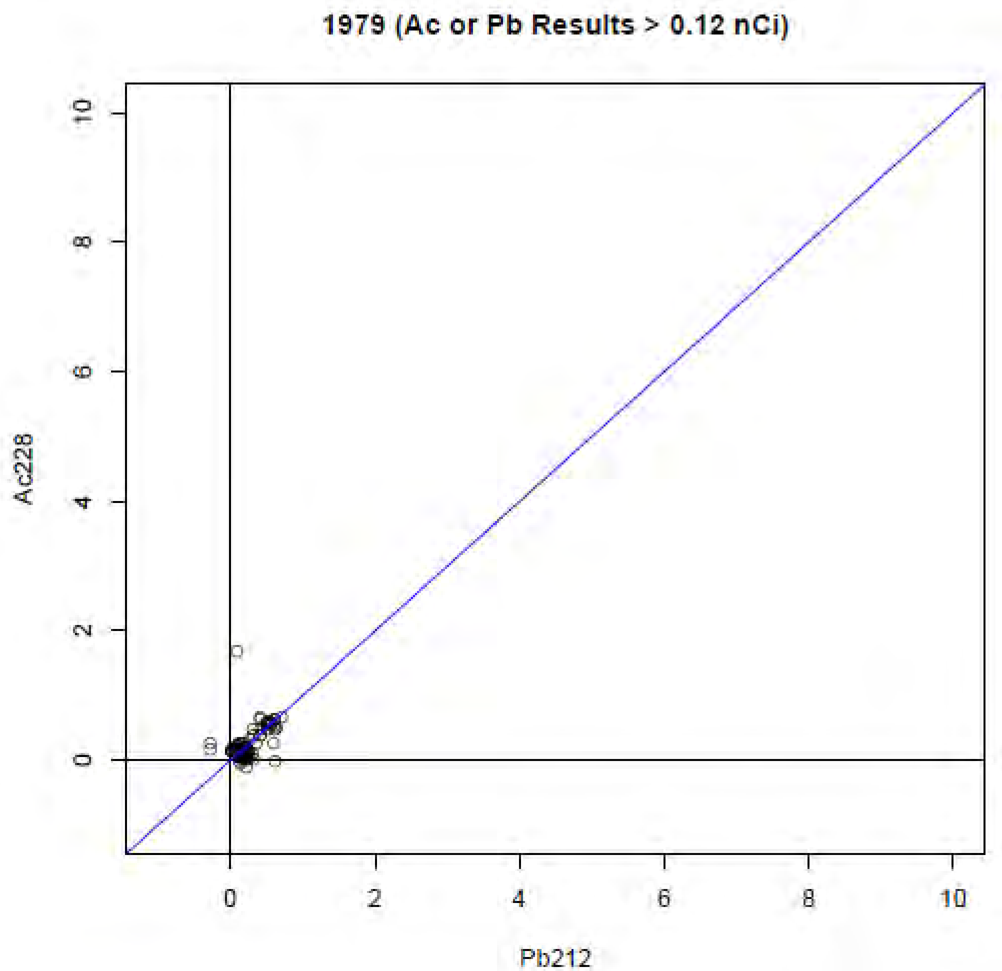
0.0
0.2
0.4
0.6
0.8
1.0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Ac228
Pb212
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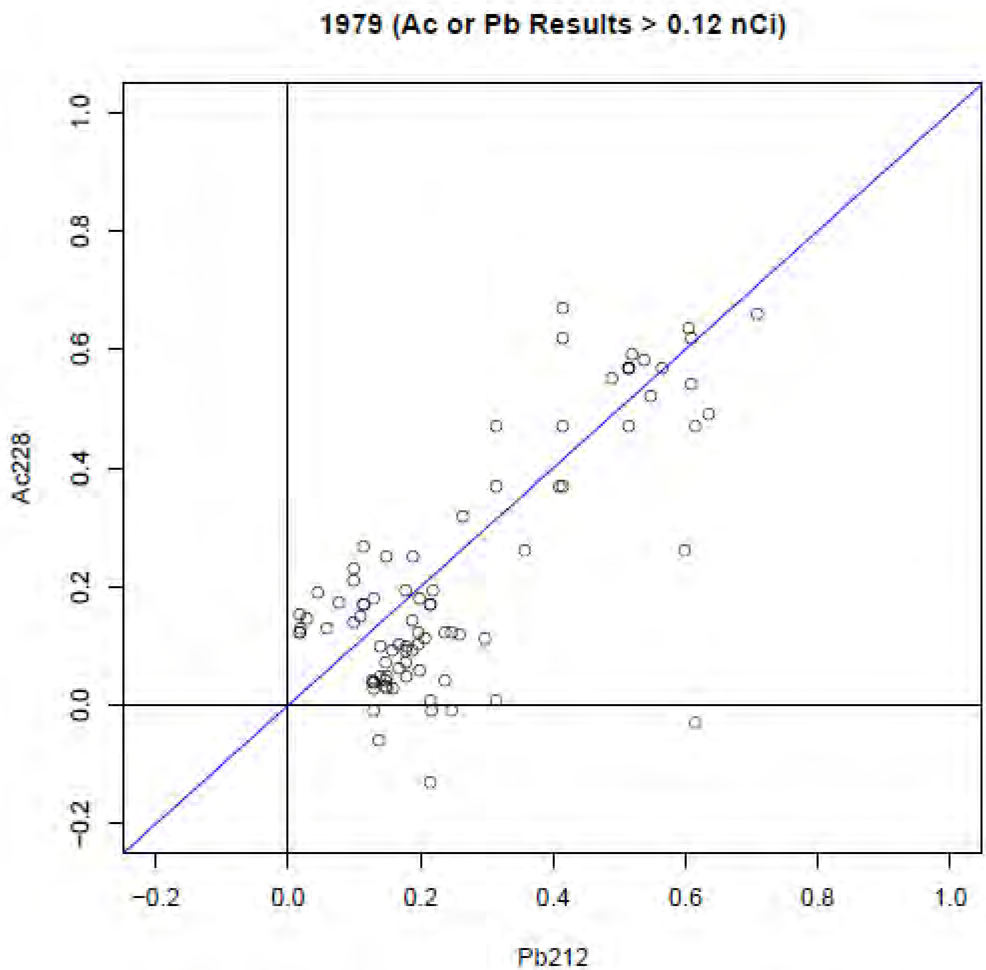
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Ac228
Pb212
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0.4
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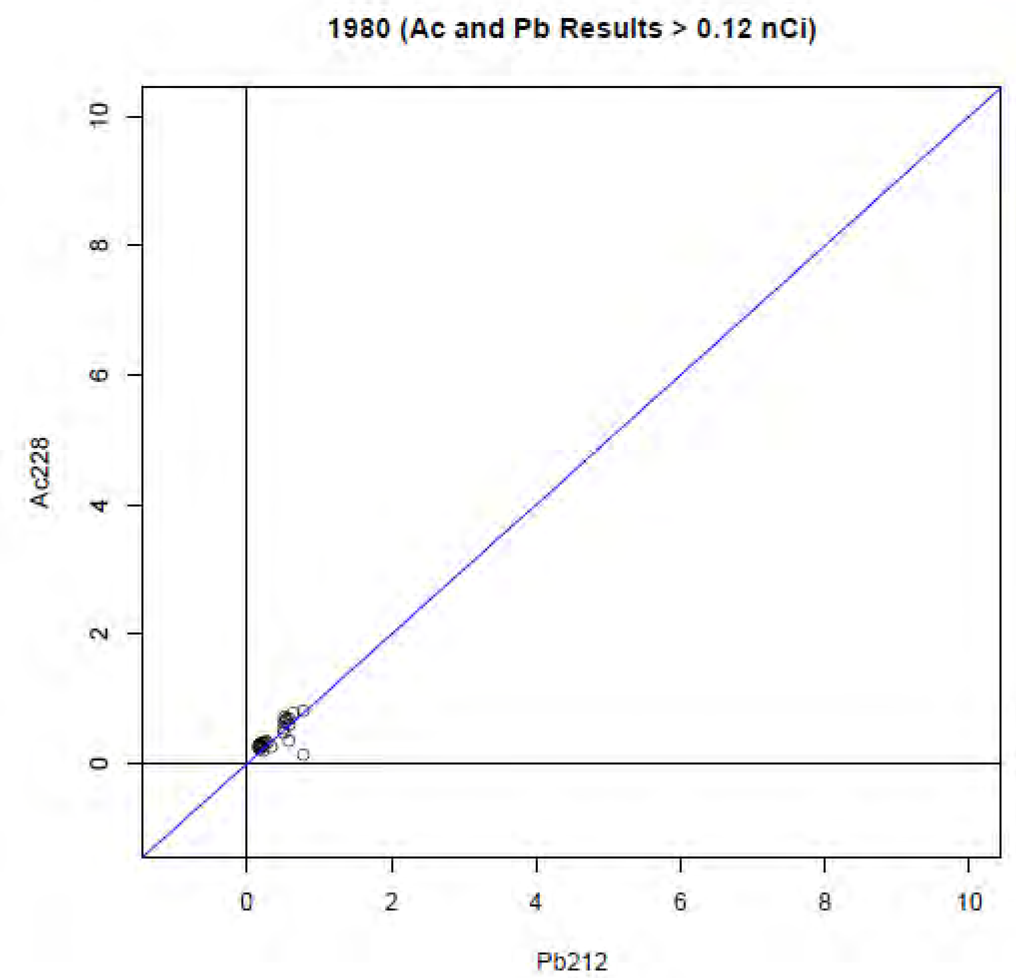
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Pb212
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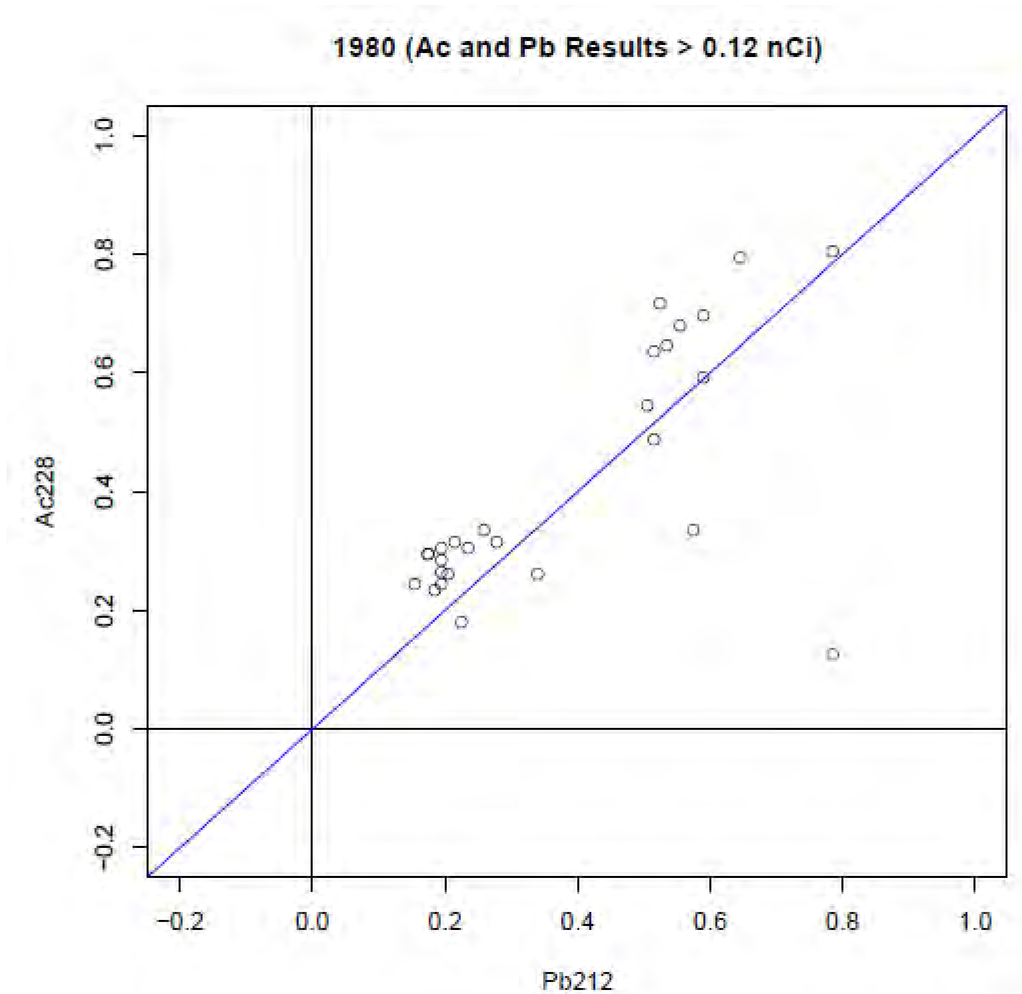
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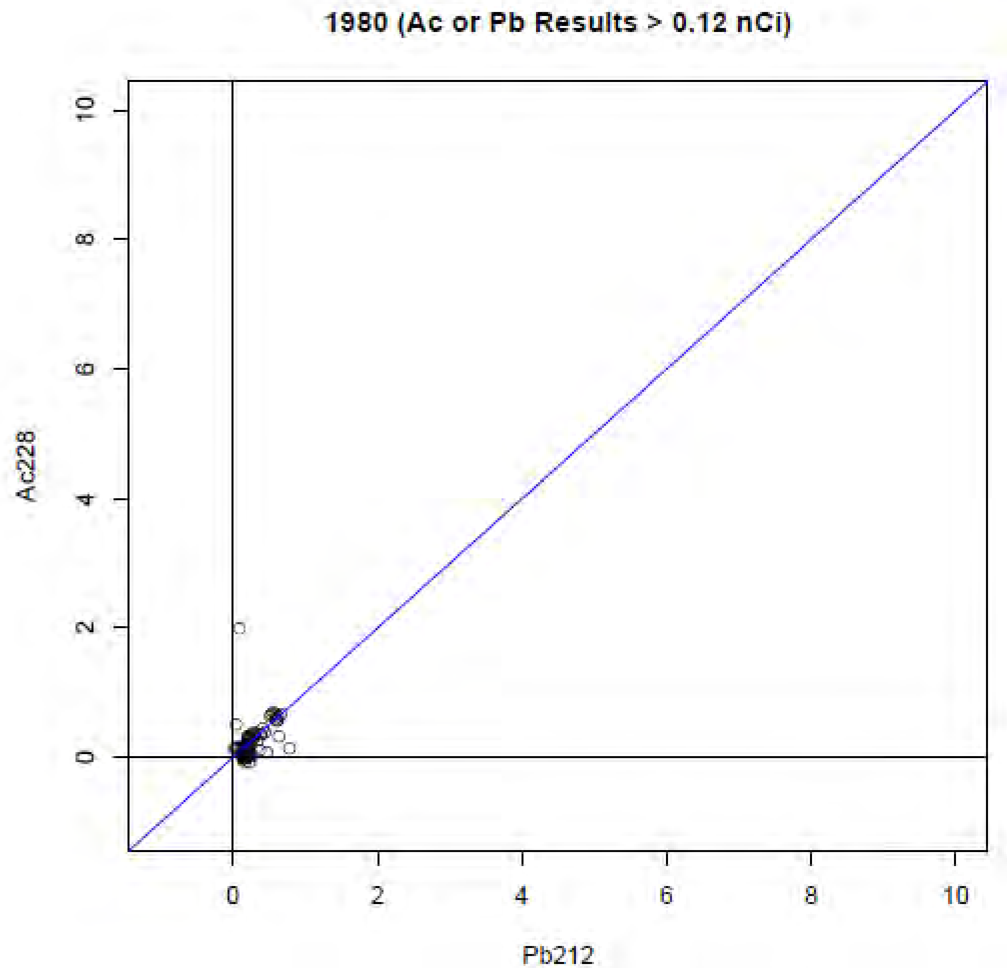
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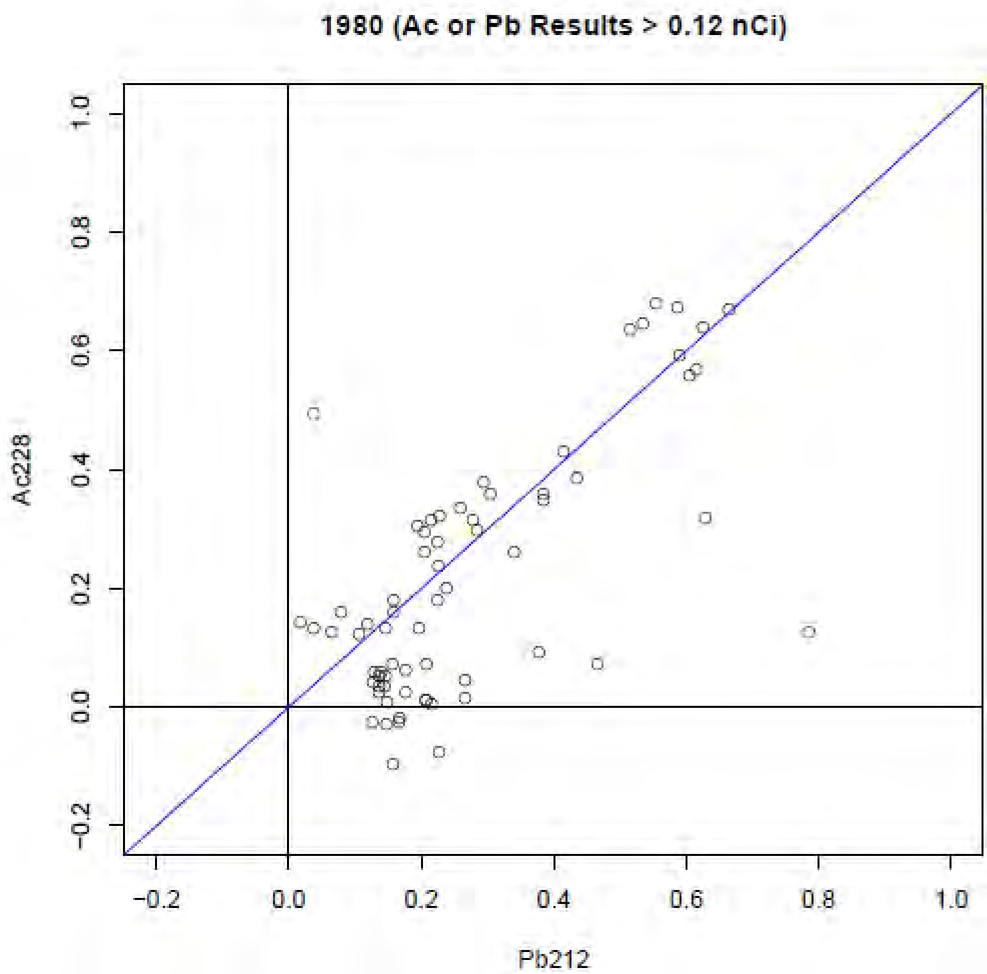
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0.2
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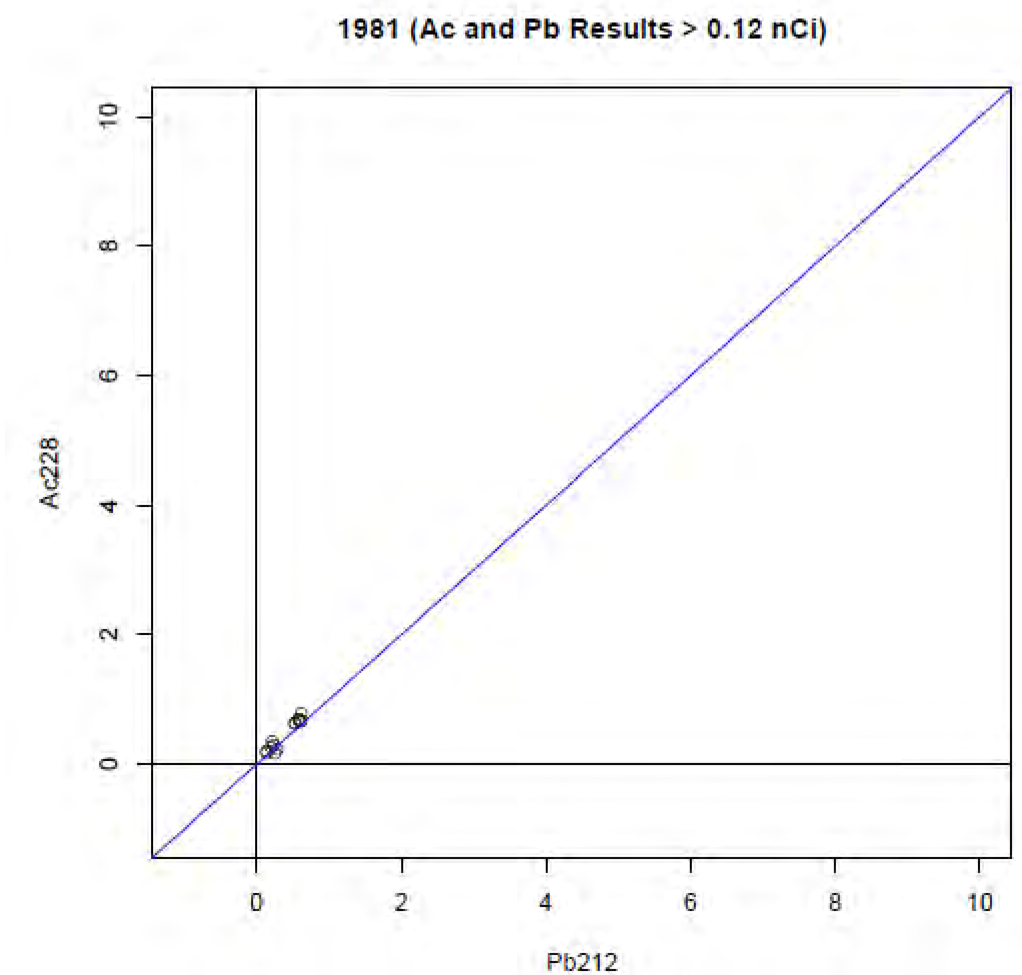
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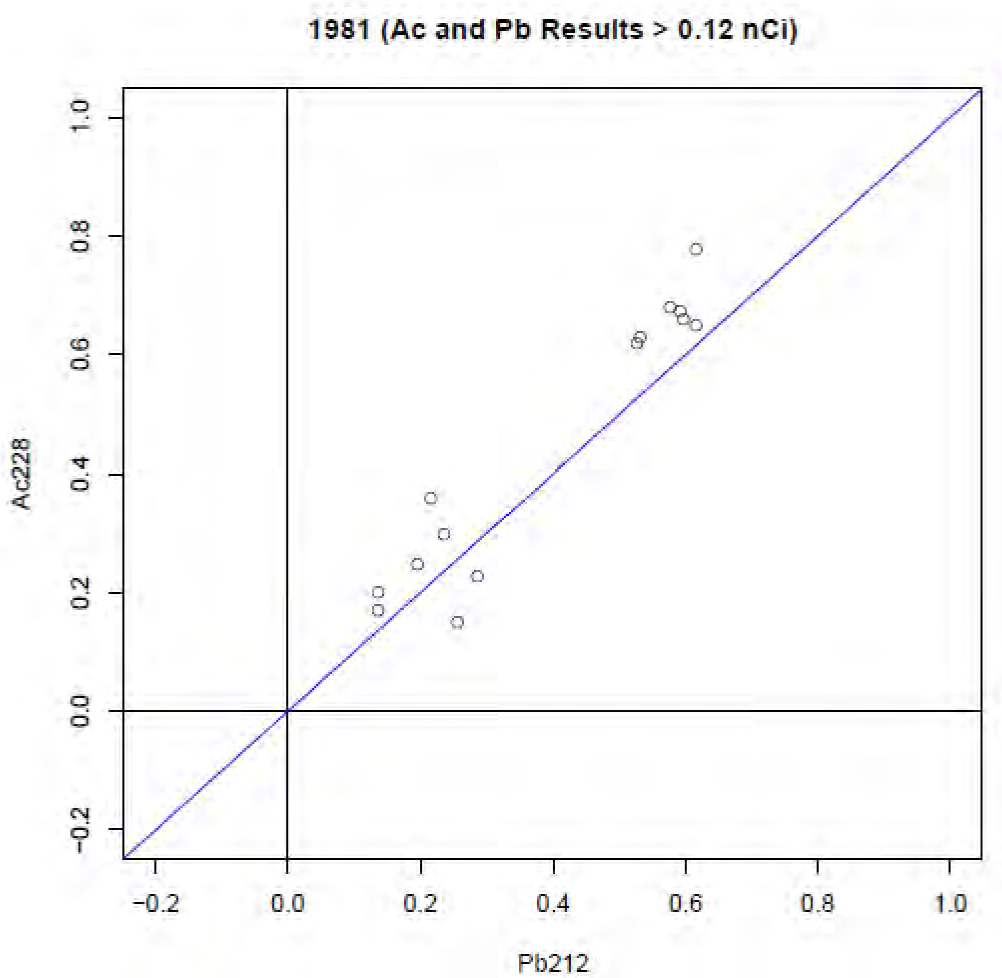
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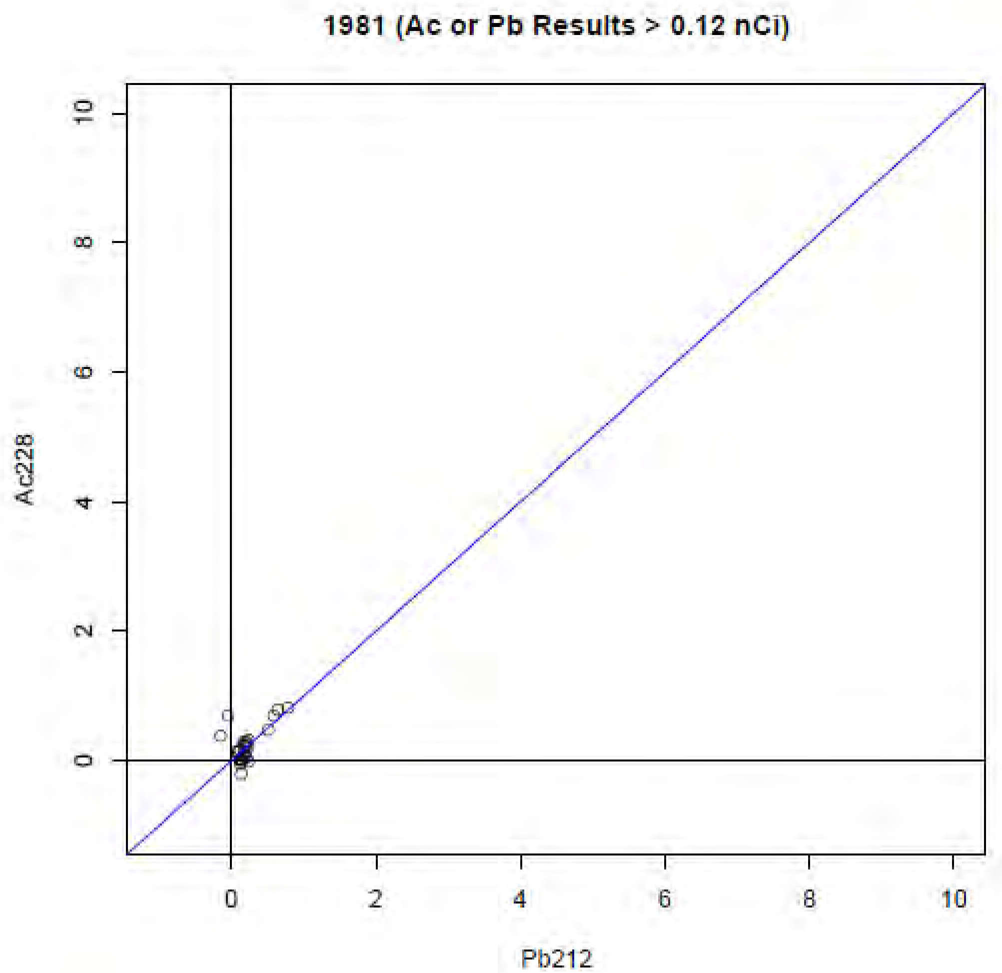
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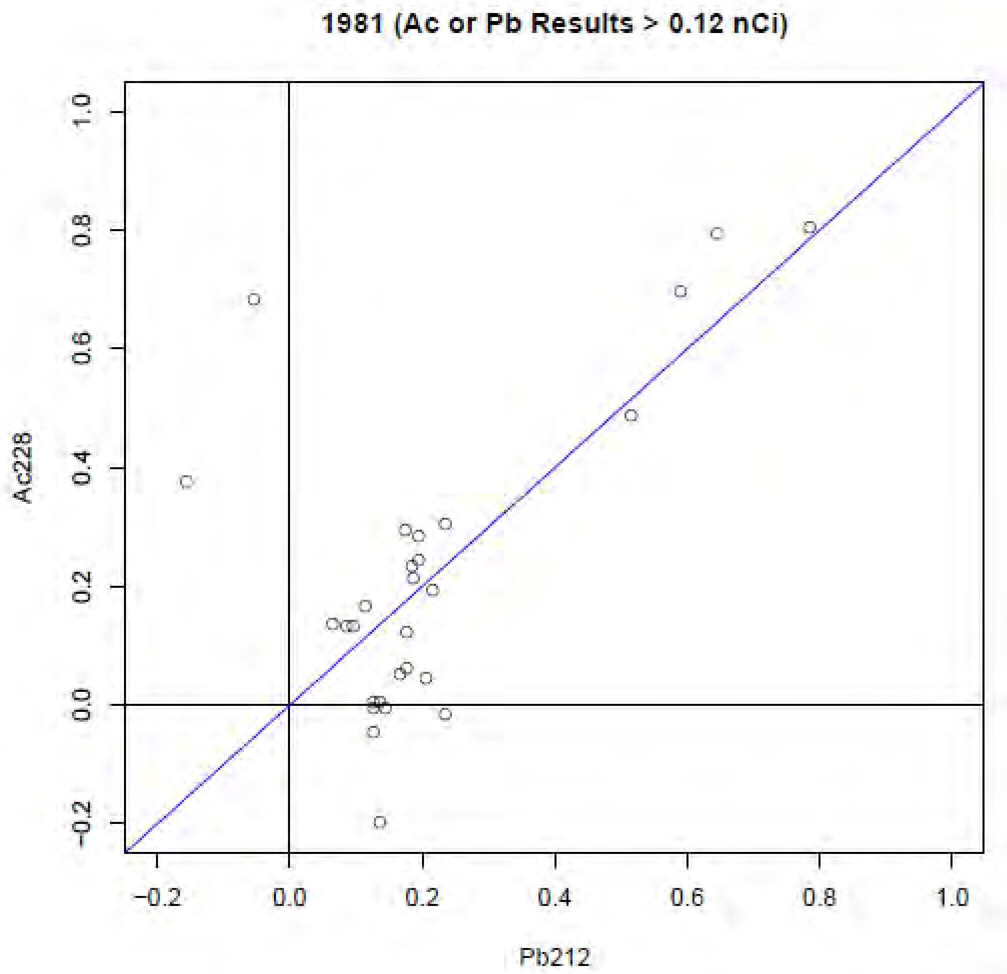
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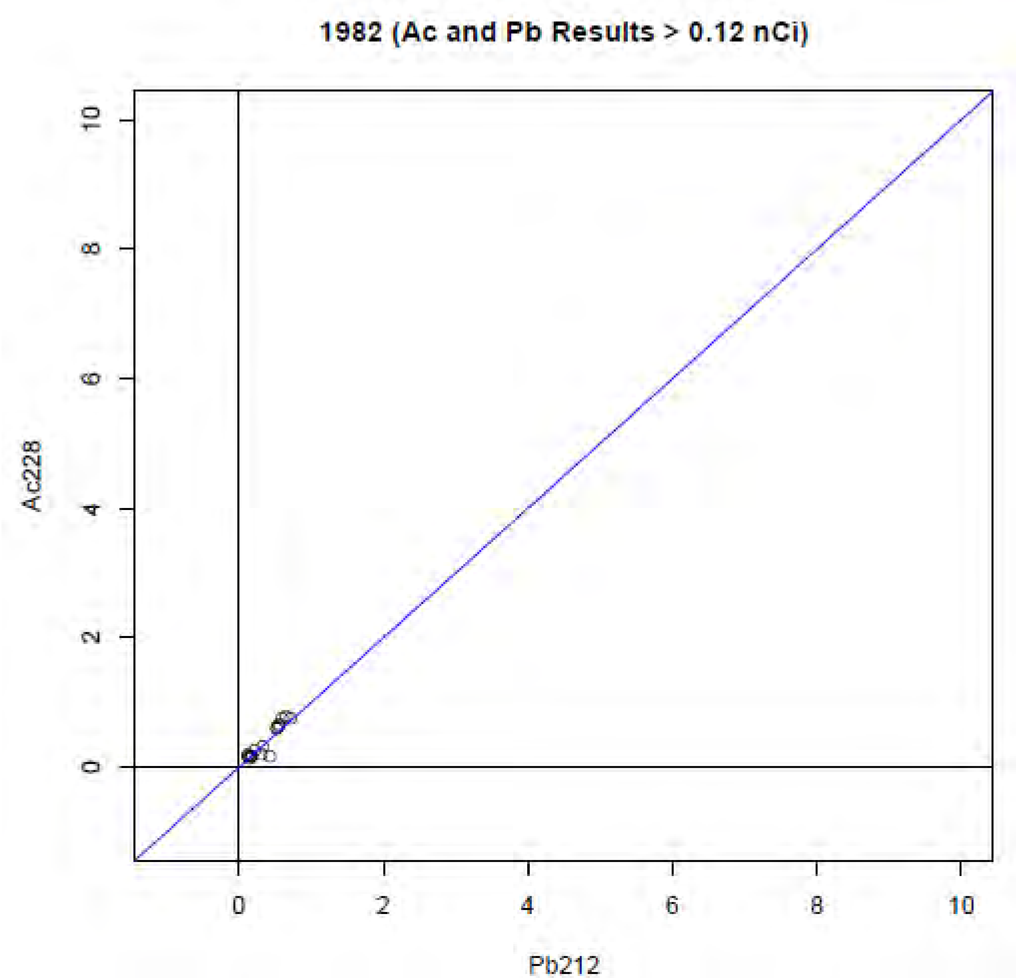
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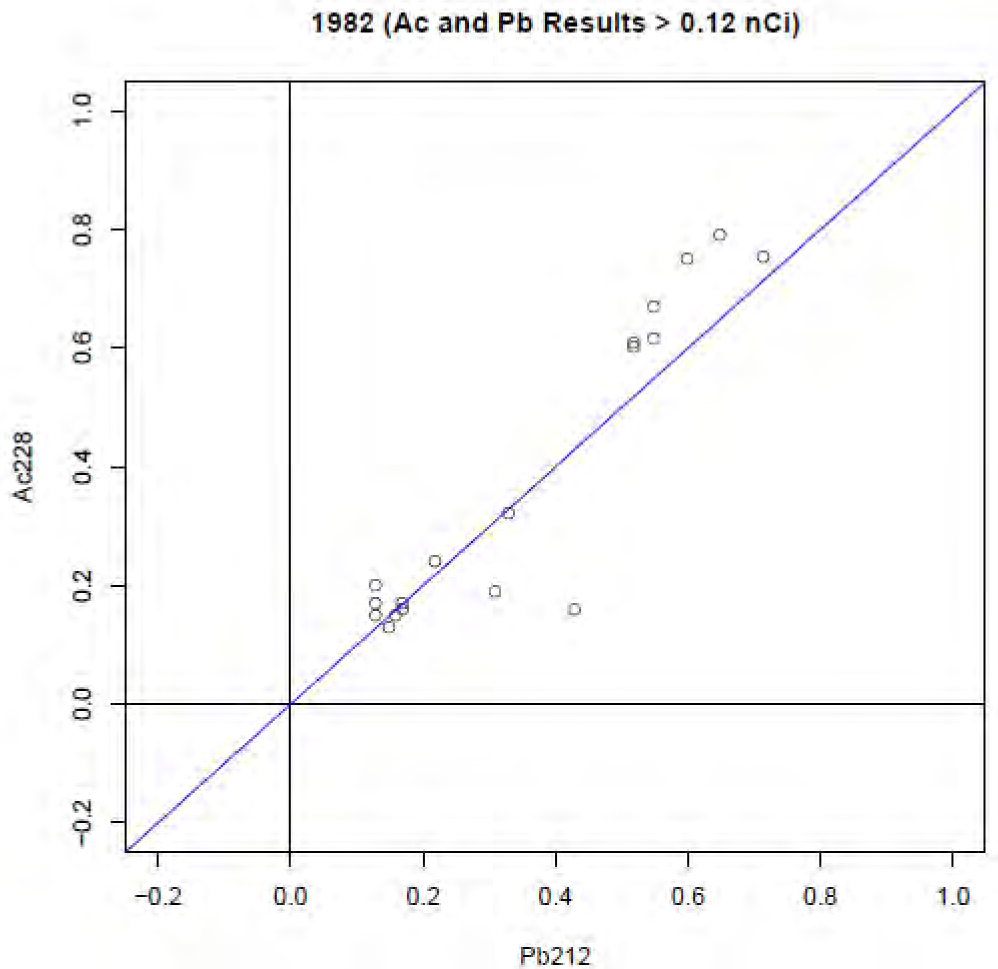
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Pb212
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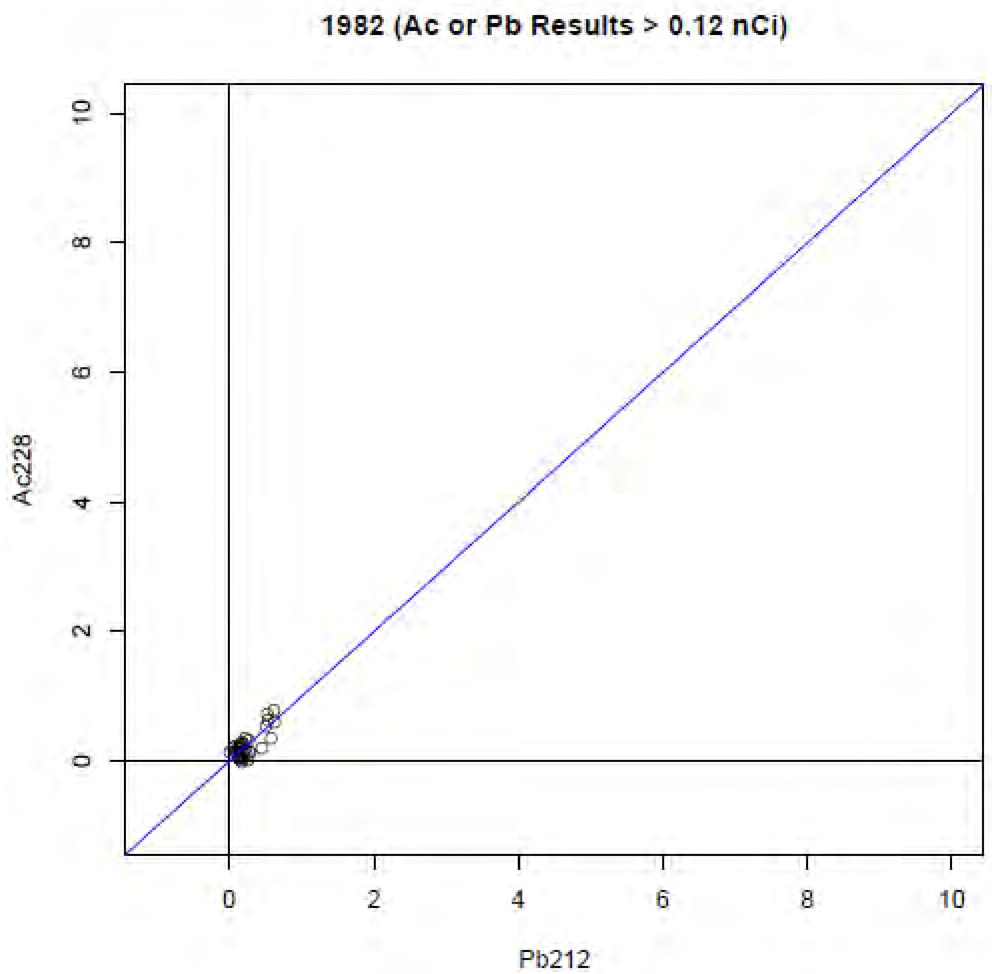
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Pb212
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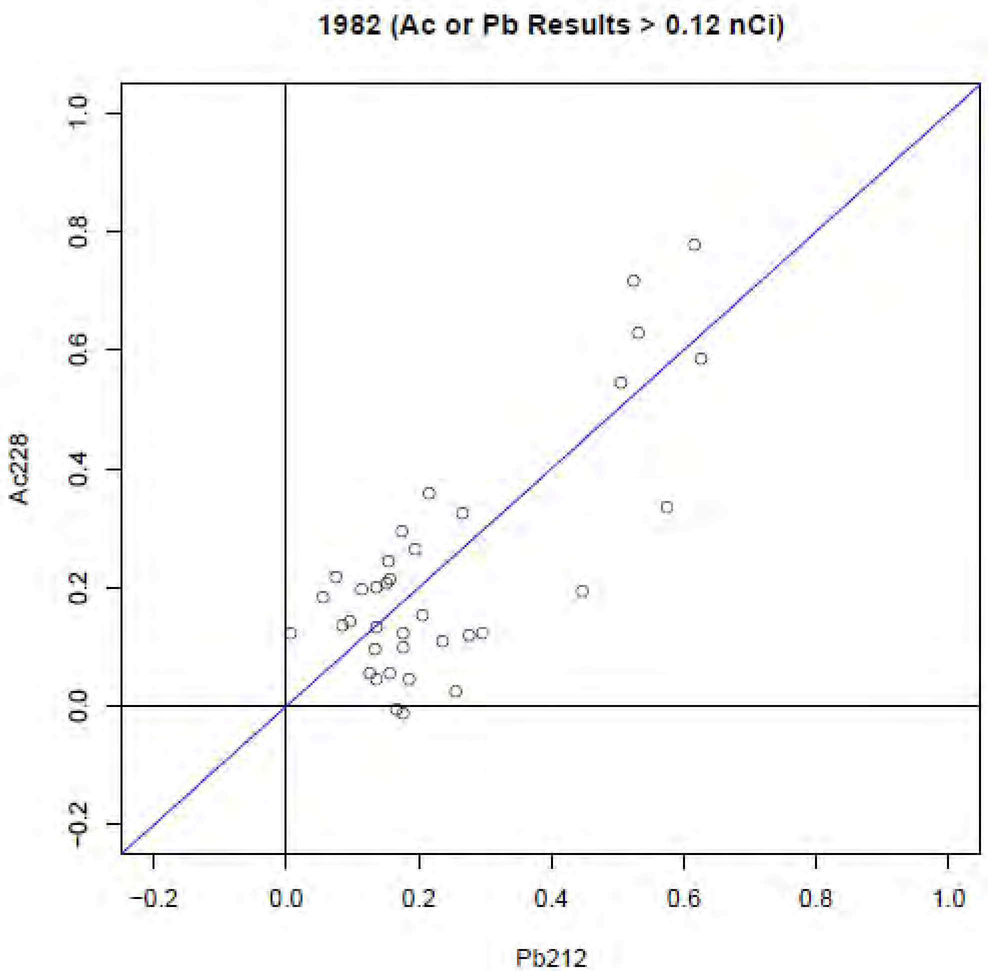
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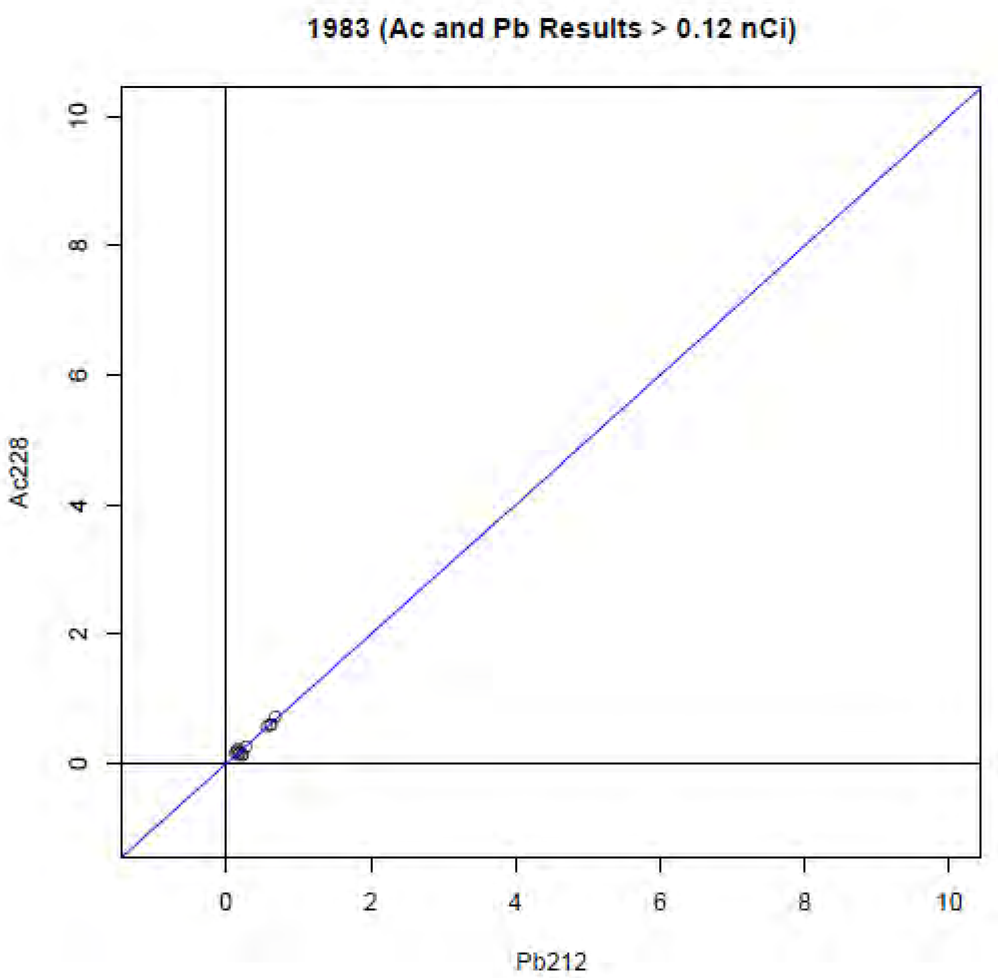
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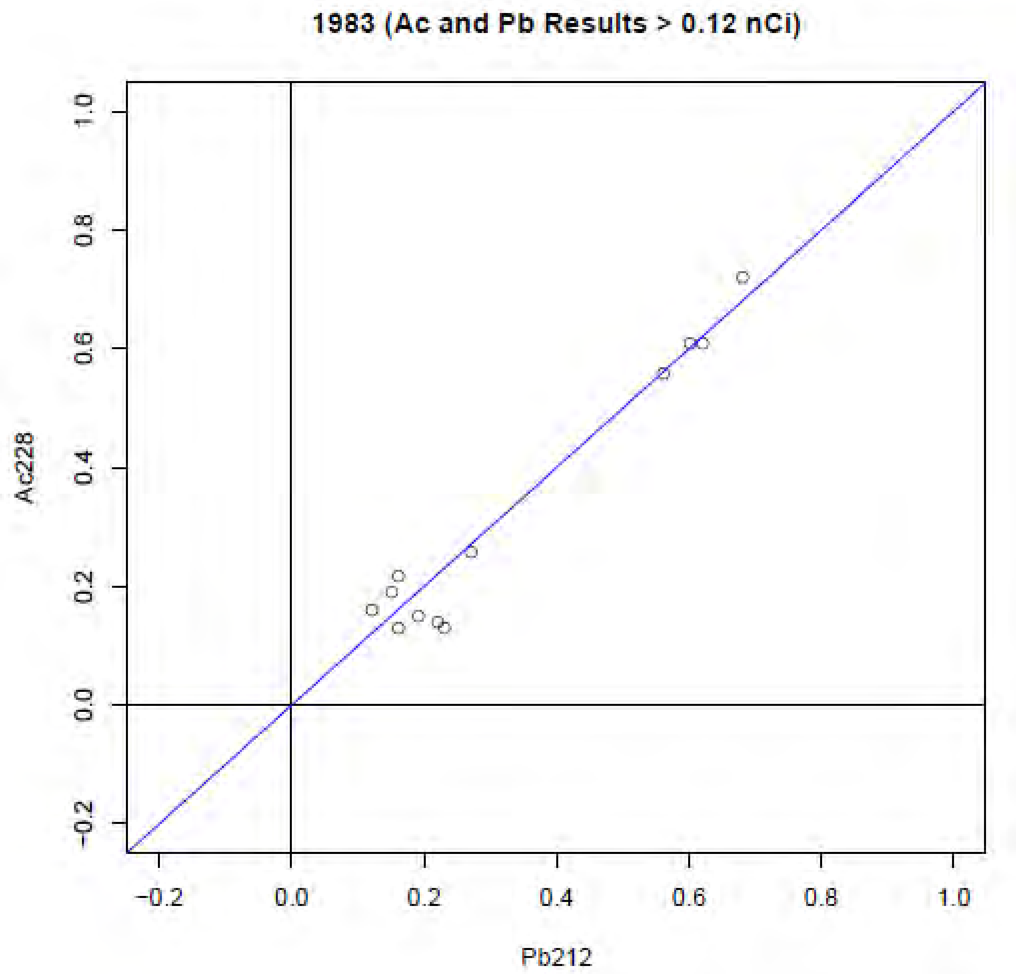
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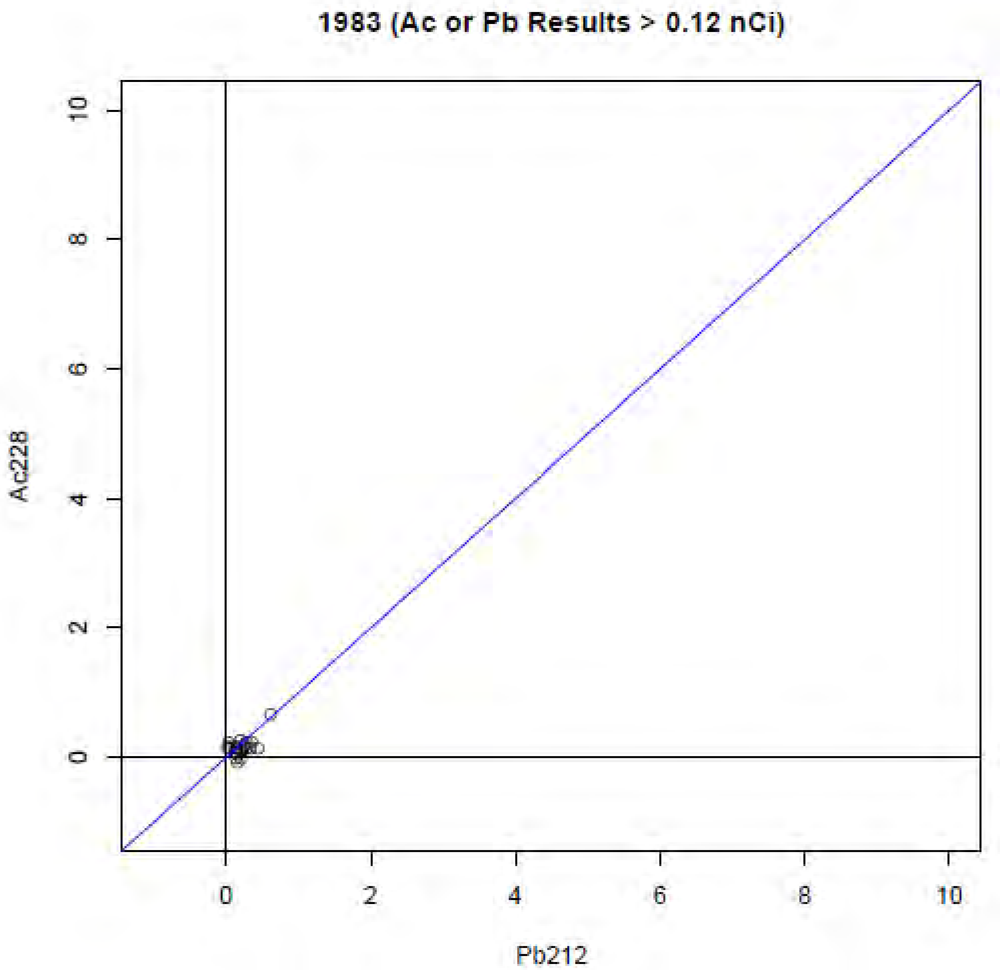
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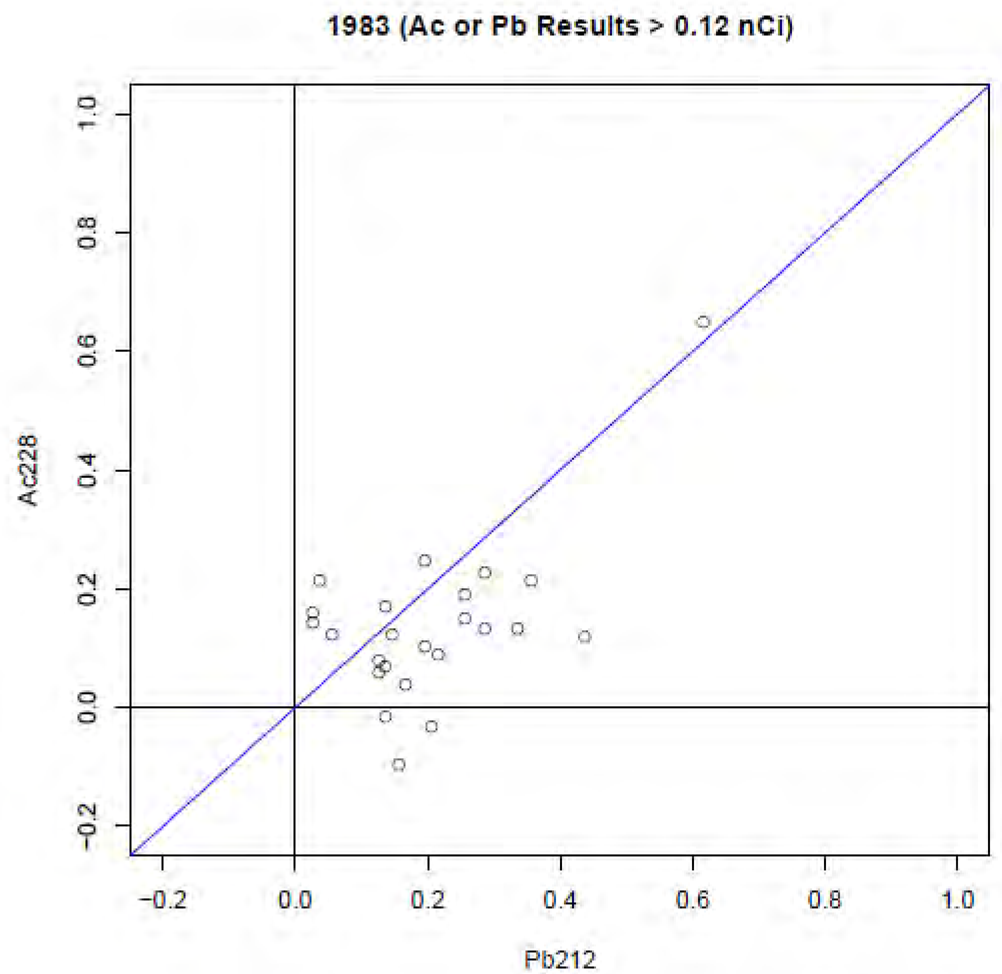
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Pb212
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0.8
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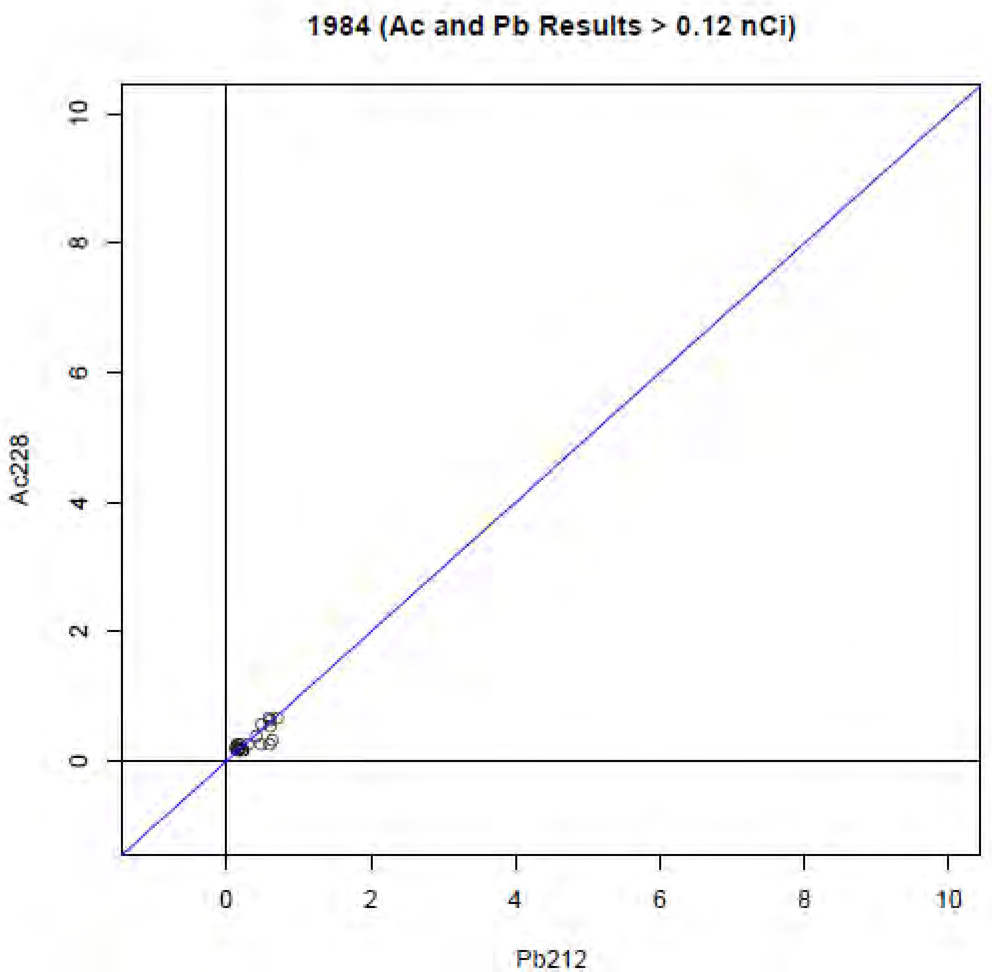
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Ac228
Pb212
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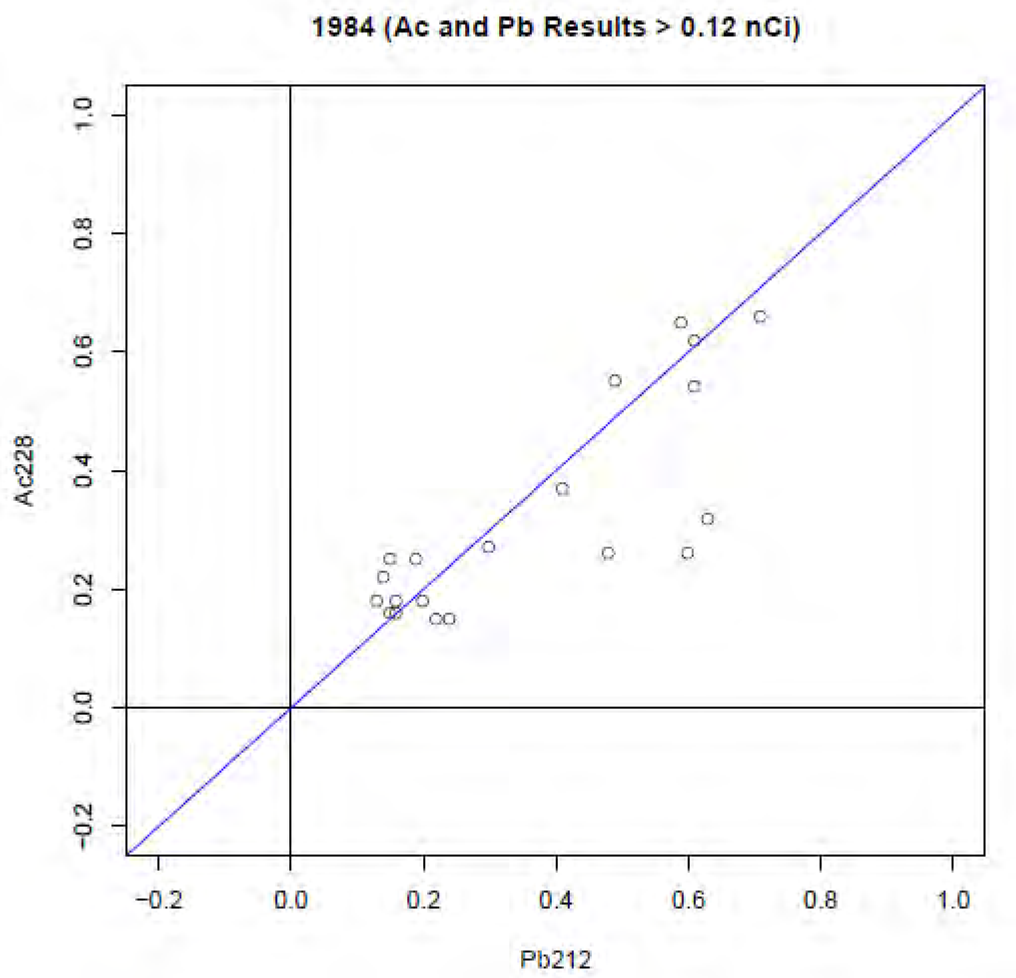
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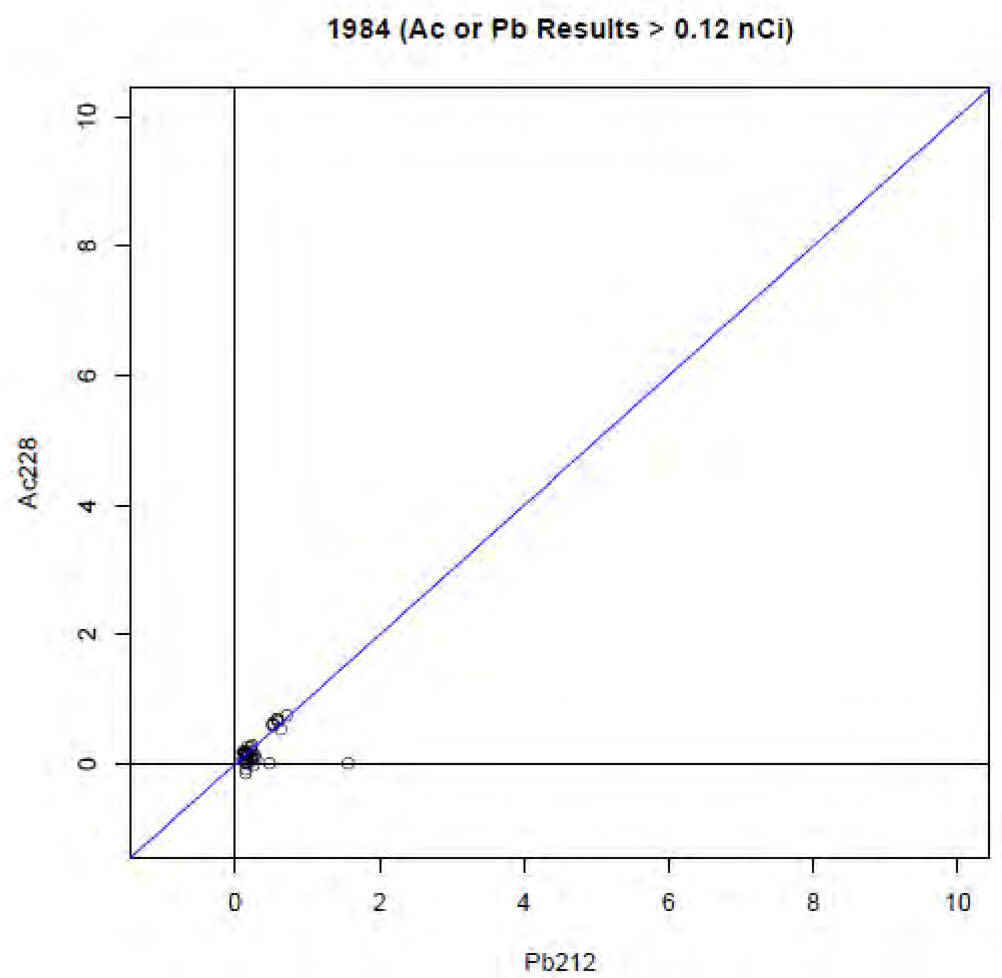
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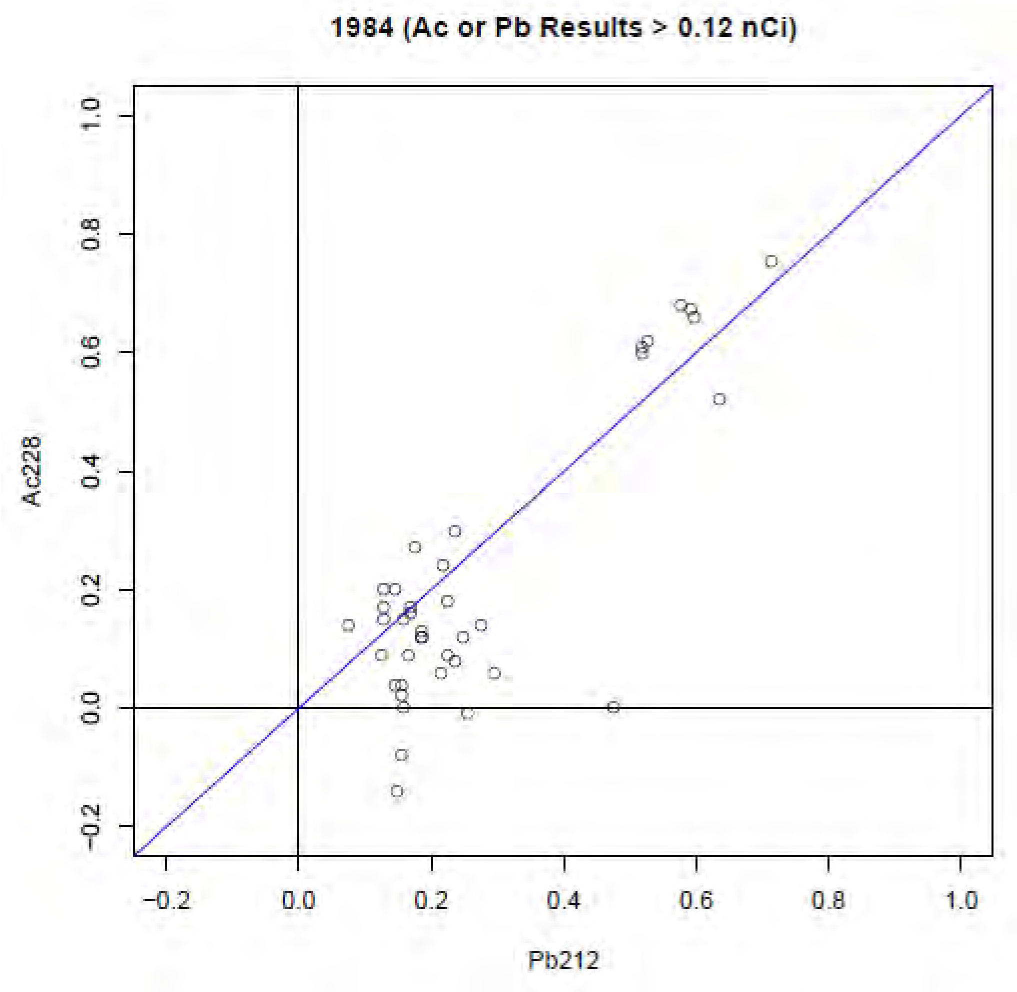
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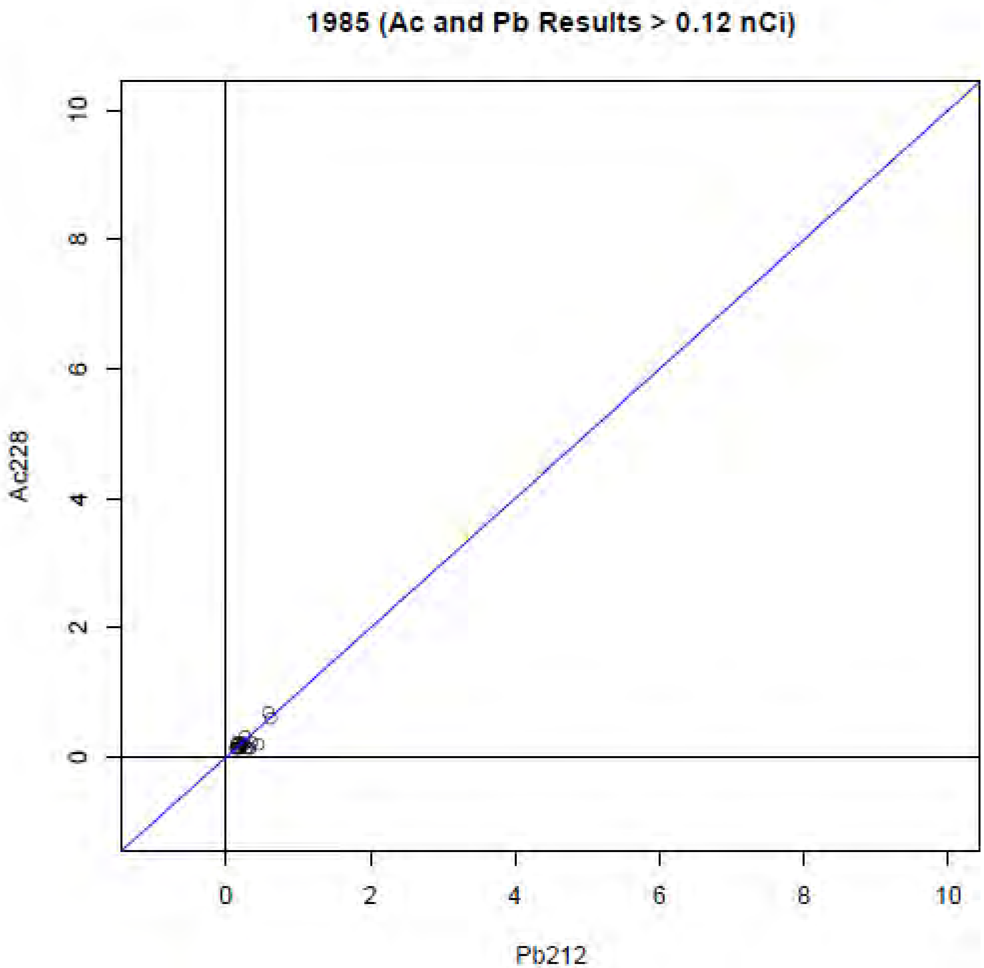
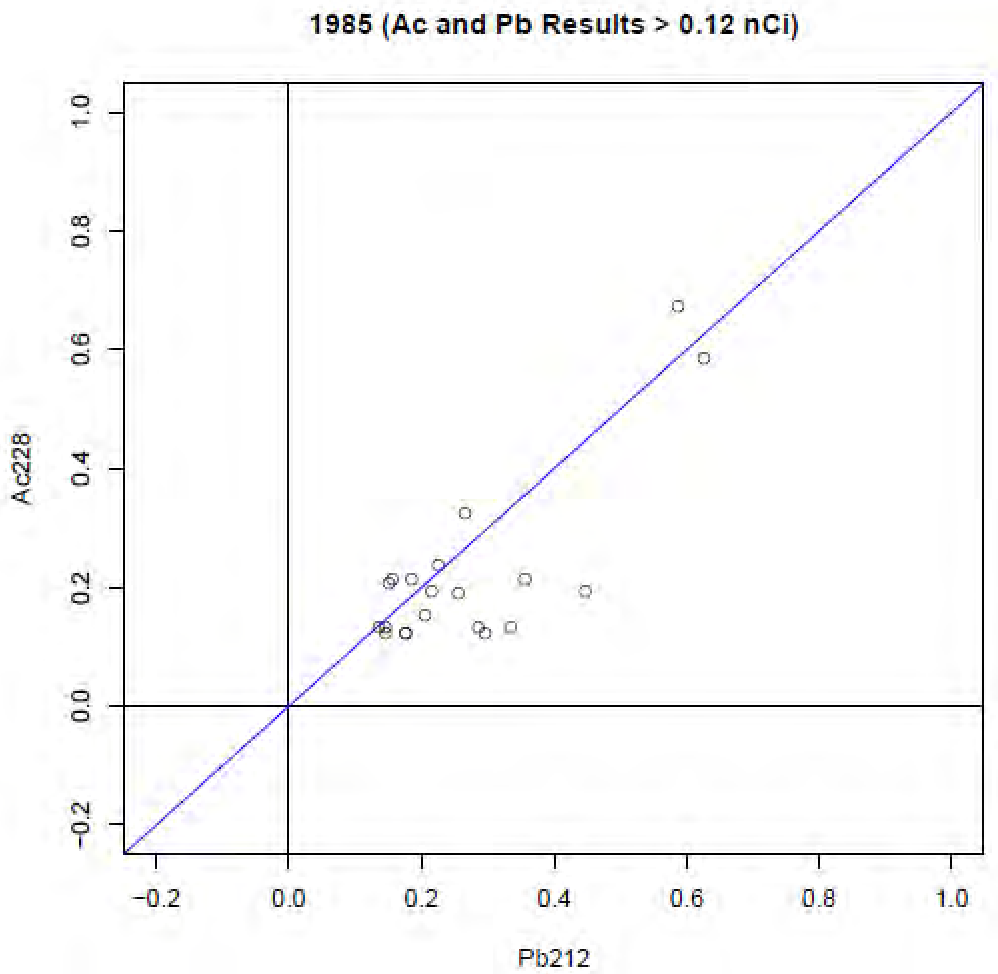
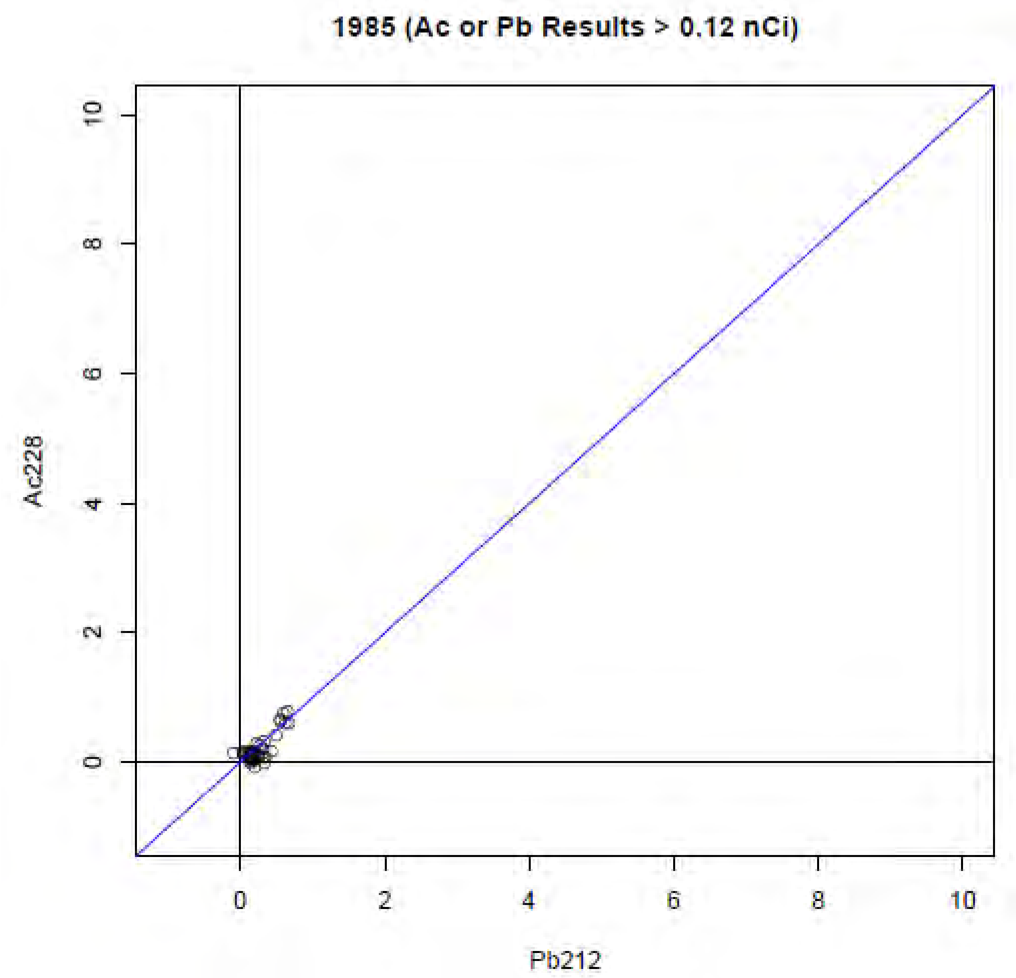
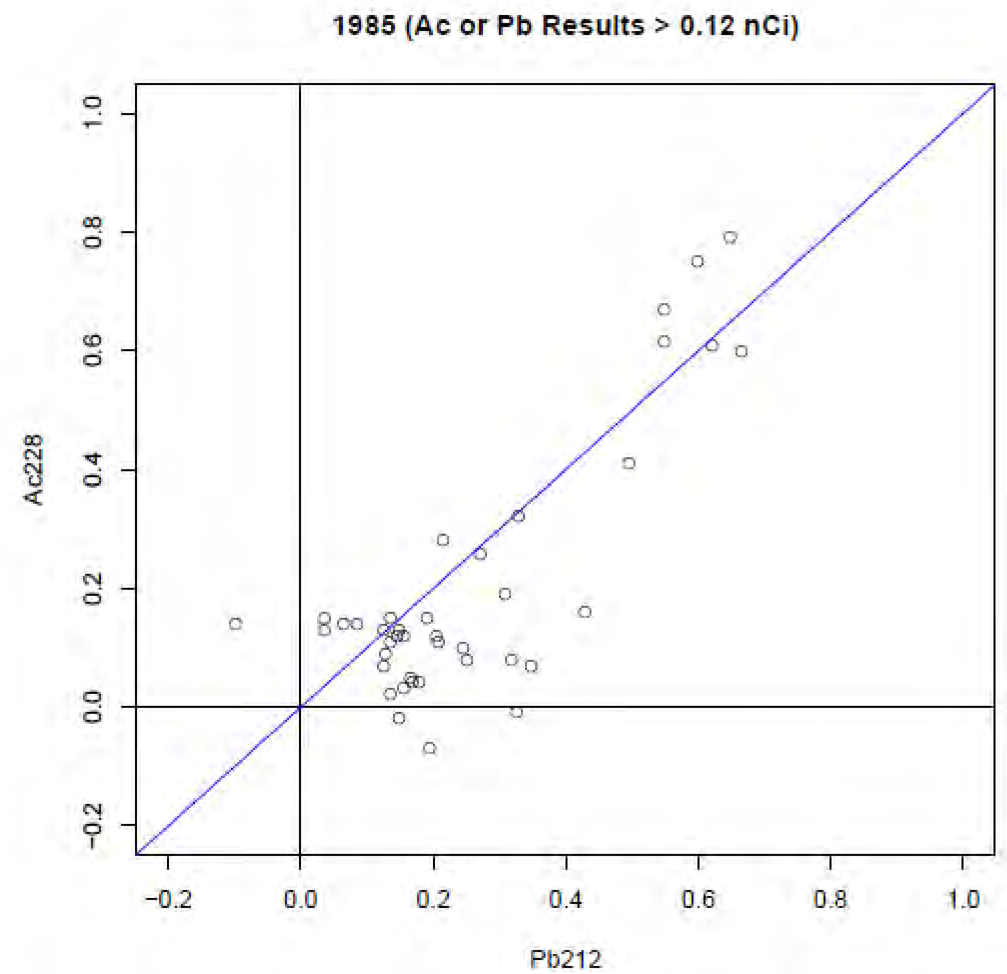
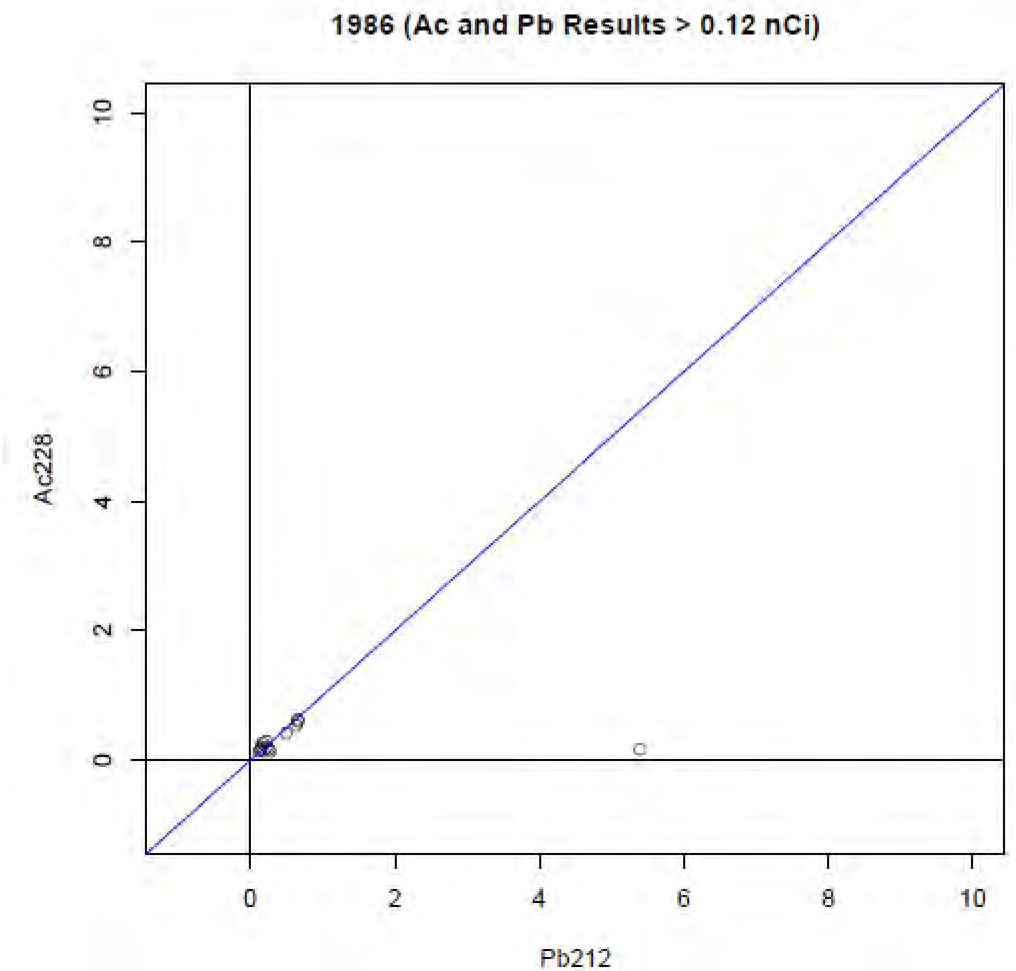
Ac228
Pb212
−0.2
0.0
0.2
0.4
0.6
0.8
1.0

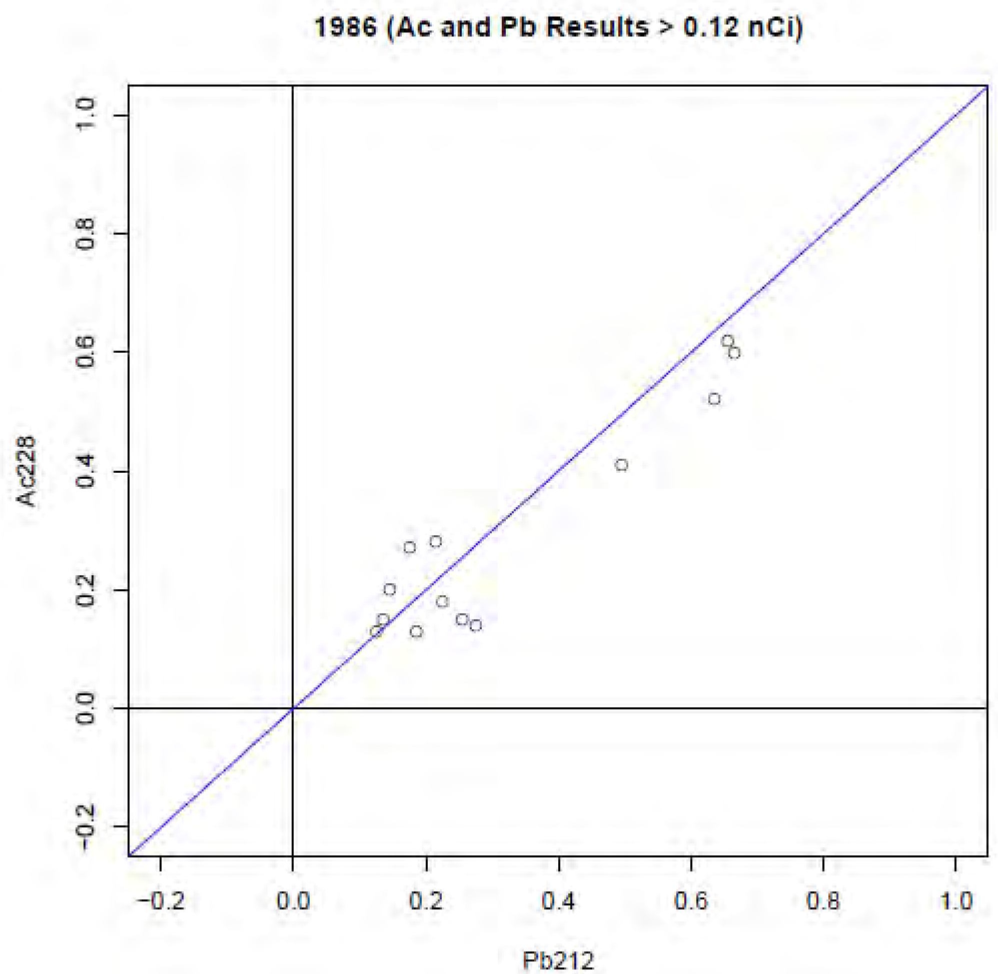

1985 (Ac and Pb Results > 0.12 nCi)
Ac228
Pb212
0
2
4
6
8
10

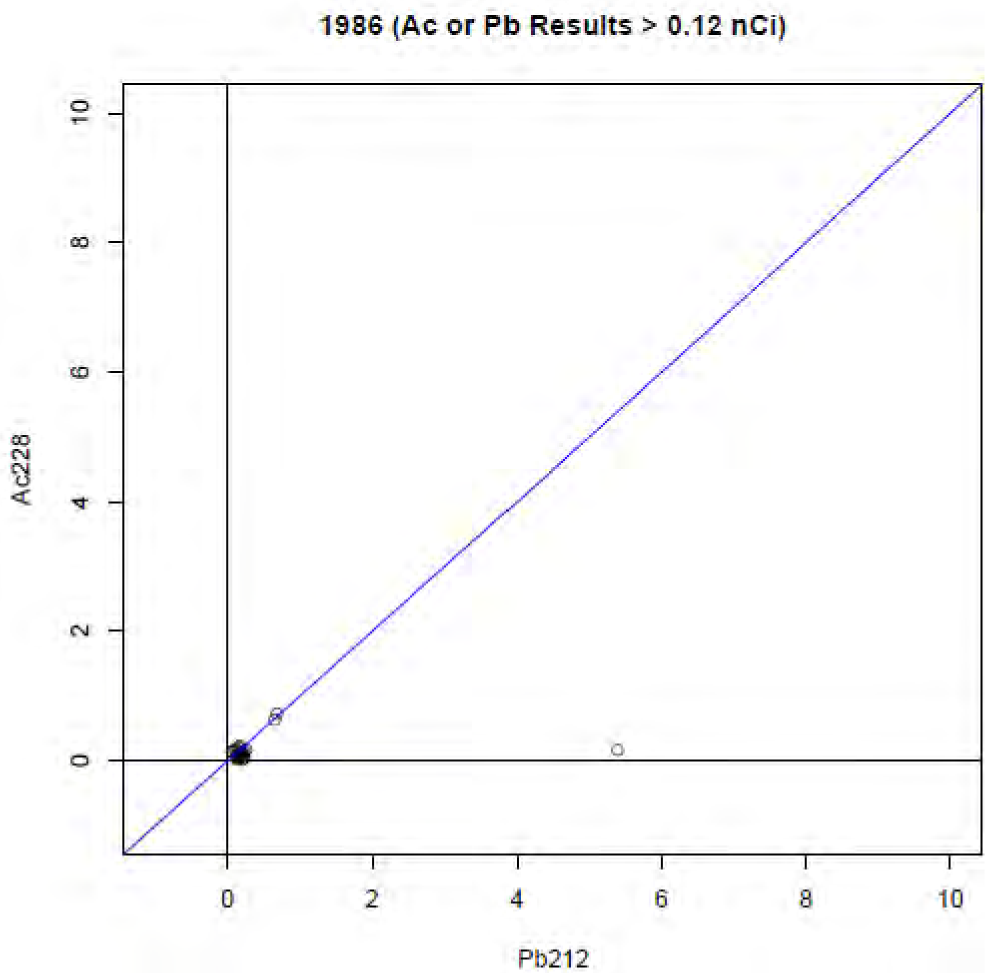

1985 (Ac and Pb Results > 0.12 nCi)
Ac228
Pb212
−0.2
0.0
0.2
0.4
0.6
0.8
1.0

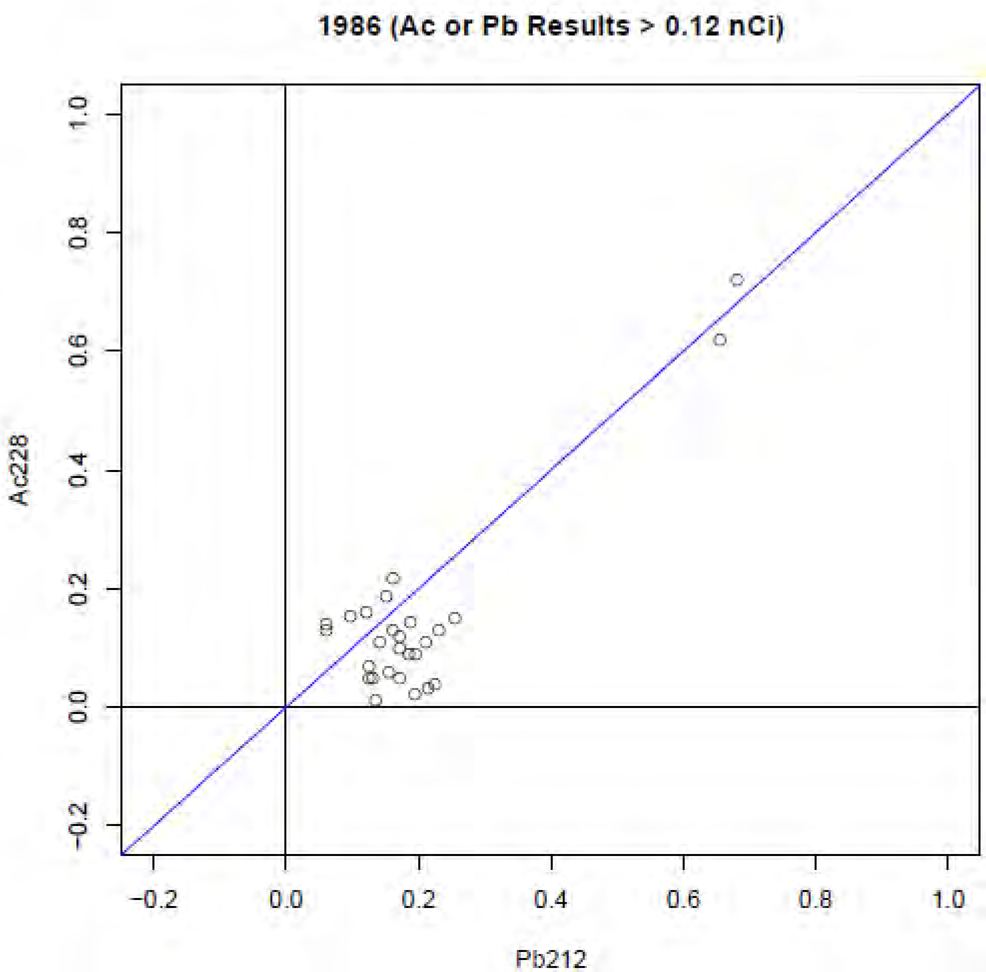

1985 (Ac or Pb Results > 0.12 nCi)
Ac228
Pb212
0
2
4
6
8
10
0
2
4
6
8
10

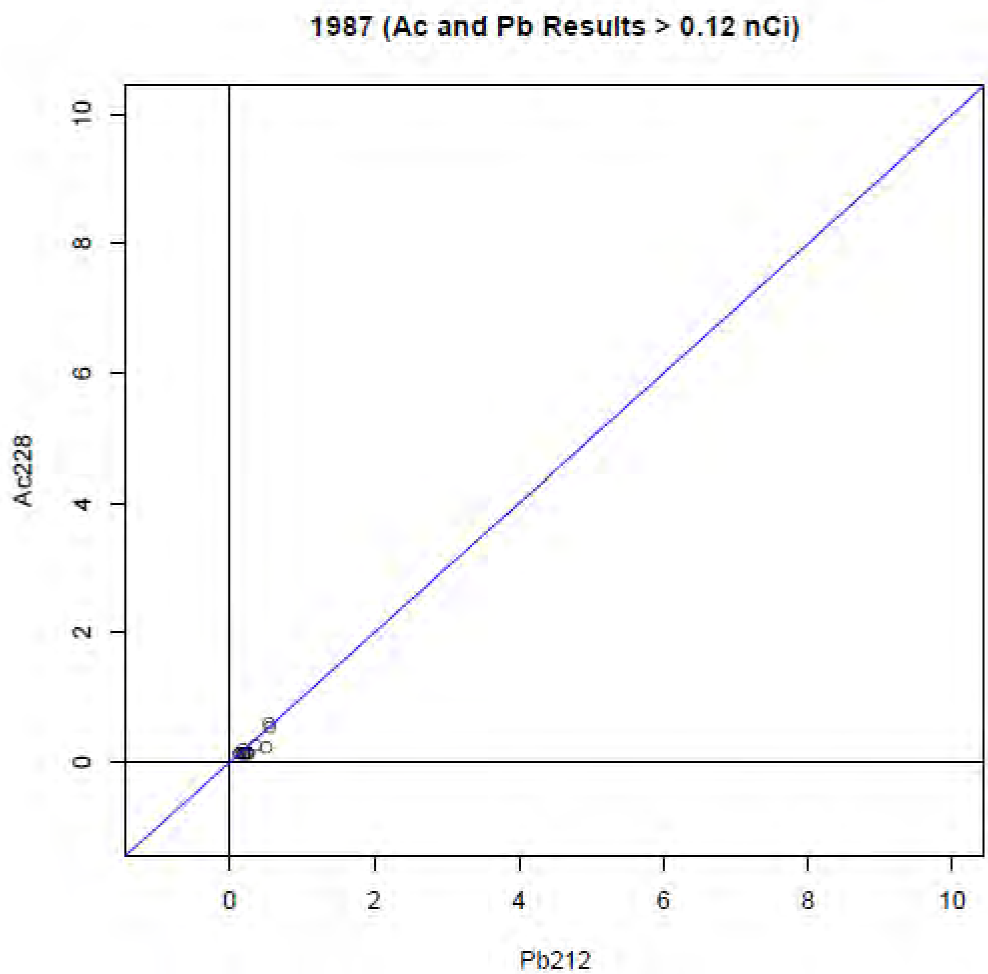

1985 (Ac or Pb Results > 0.12 nCi)
Ac228
Pb212
−0.2
0.0
0.2
0.4
0.6
0.8
1.0

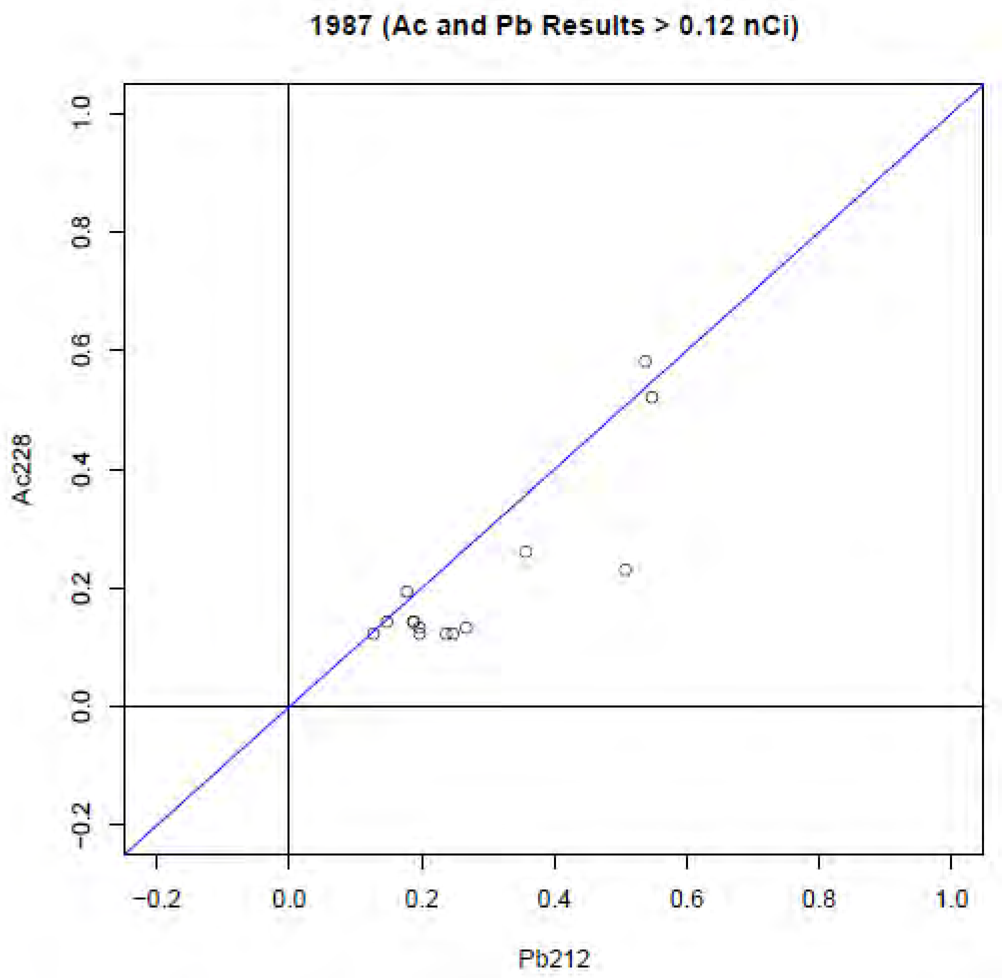

1986 (Ac and Pb Results > 0.12 nCi)
Ac228
Pb212
0
2
4
6
8
10

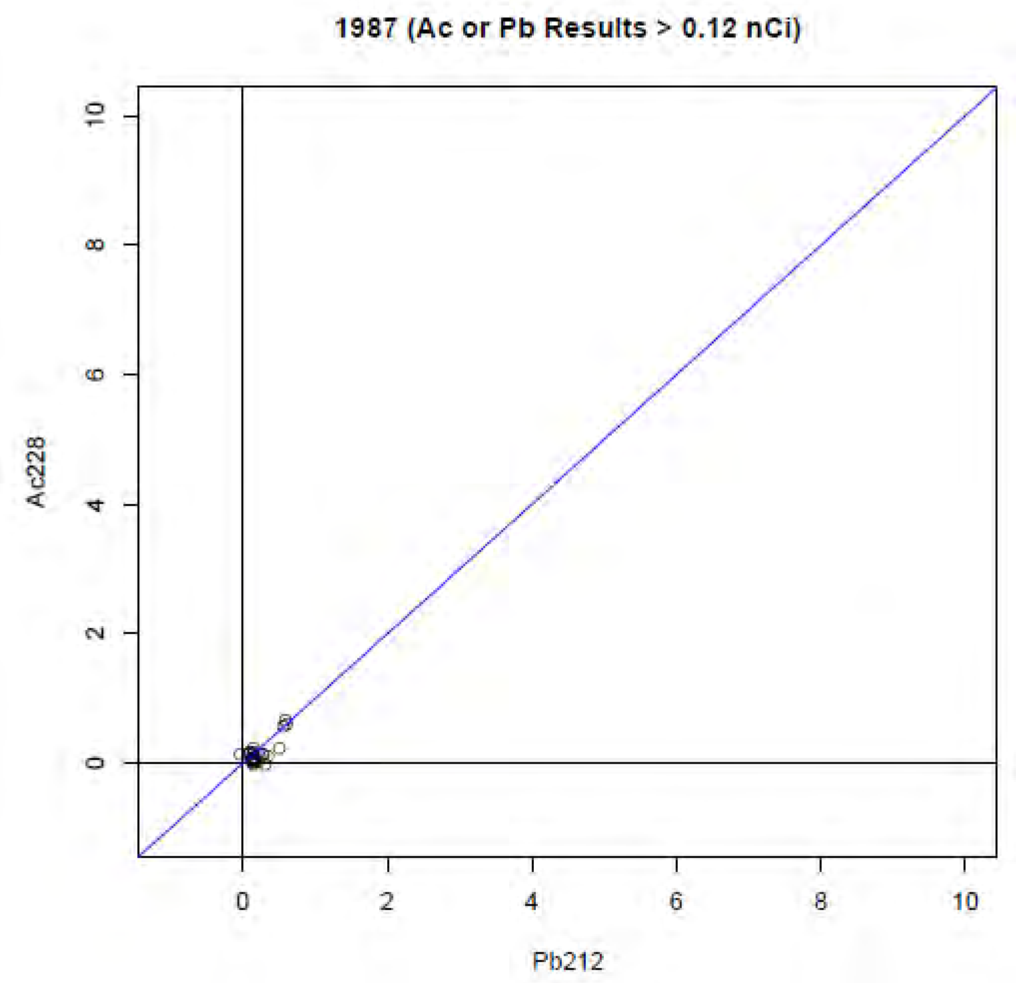

1986 (Ac and Pb Results > 0.12 nCi)
Ac228
Pb212
-0.2
0.0
0.2
0.4
0.6
0.8
1.0

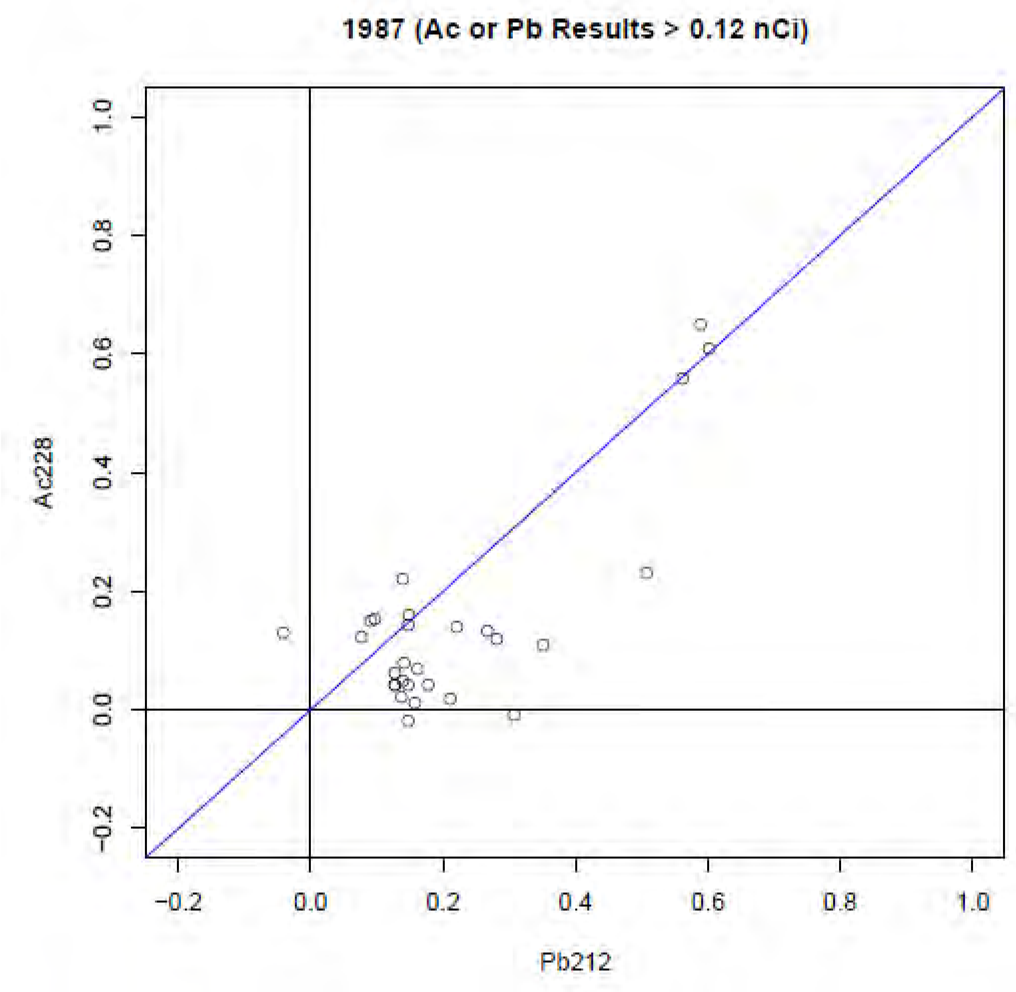

1986 (Ac or Pb Results > 0.12 nCi)
Ac228
Pb212
0
2
4
6
8
10

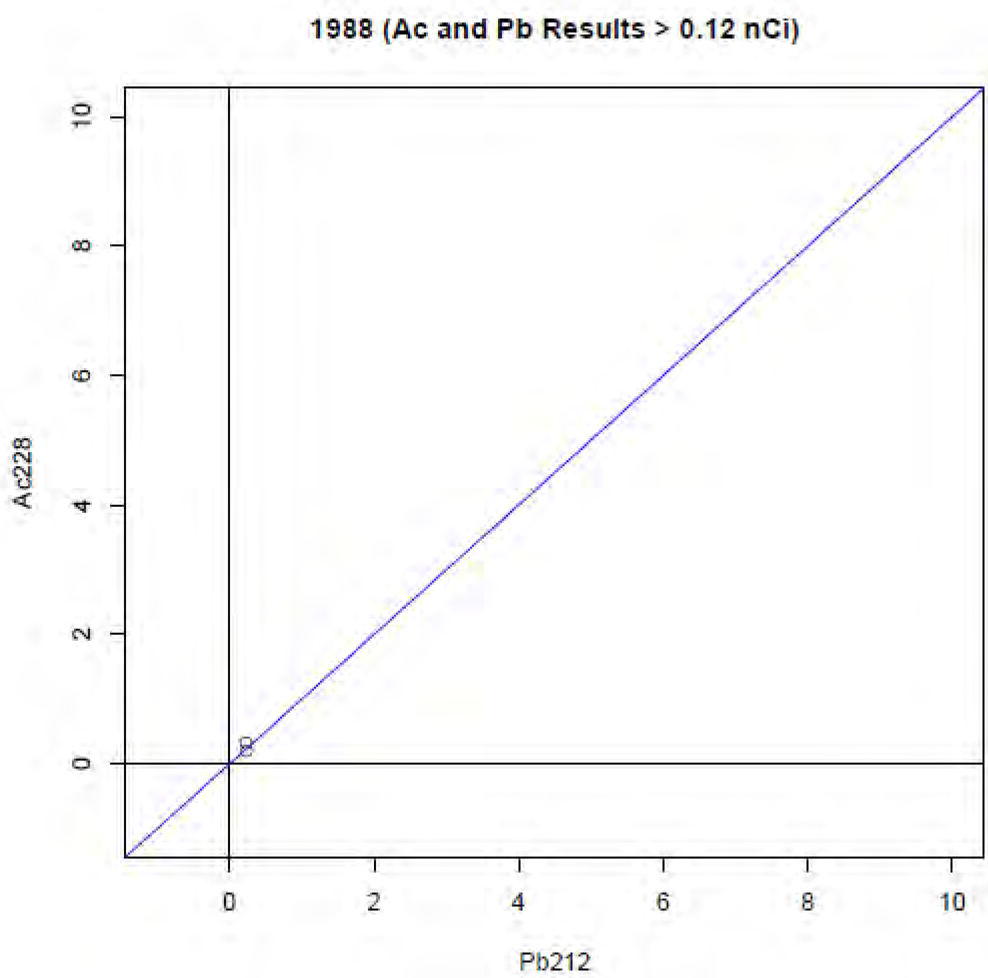

1986 (Ac or Pb Results > 0.12 nCi)
Ac228
Pb212
−0.2
0.0
0.2
0.4
0.6
0.8
1.0

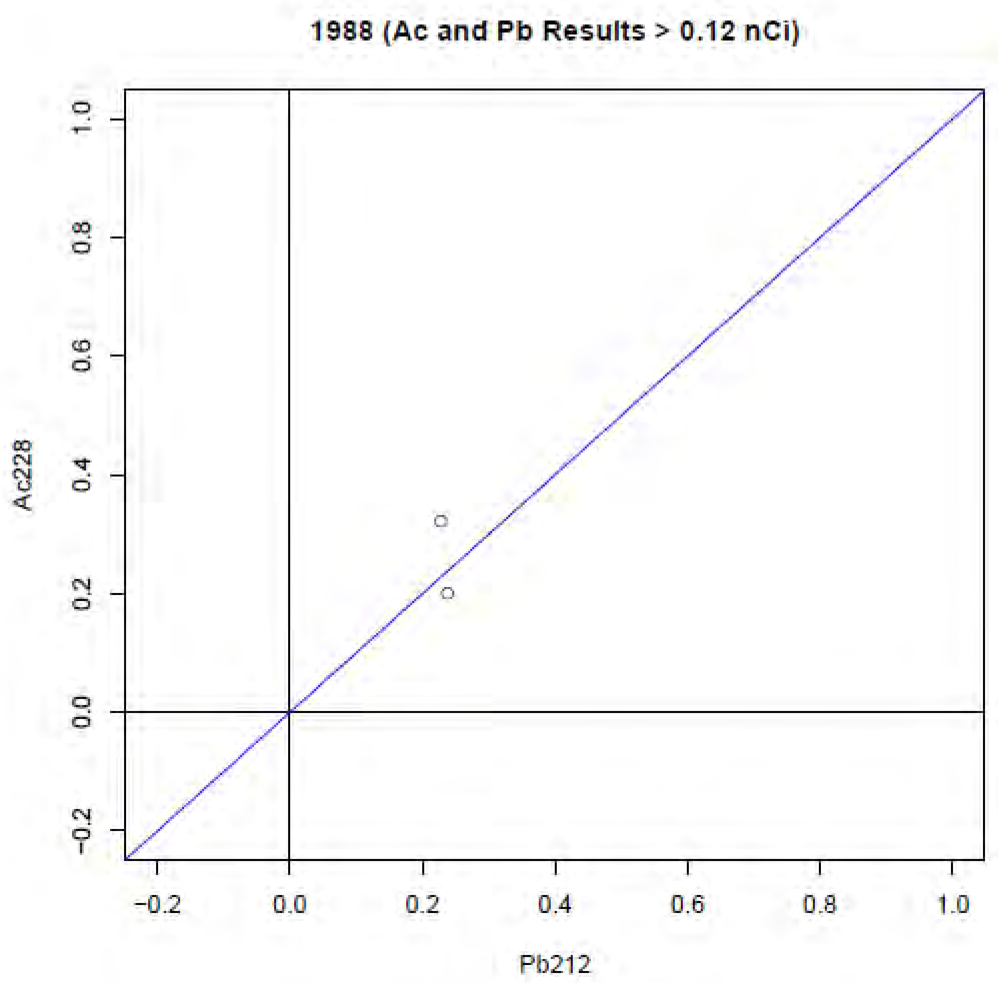

1987 (Ac and Pb Results > 0.12 nCi)
Ac228
Pb212
0
2
4
6
8
10

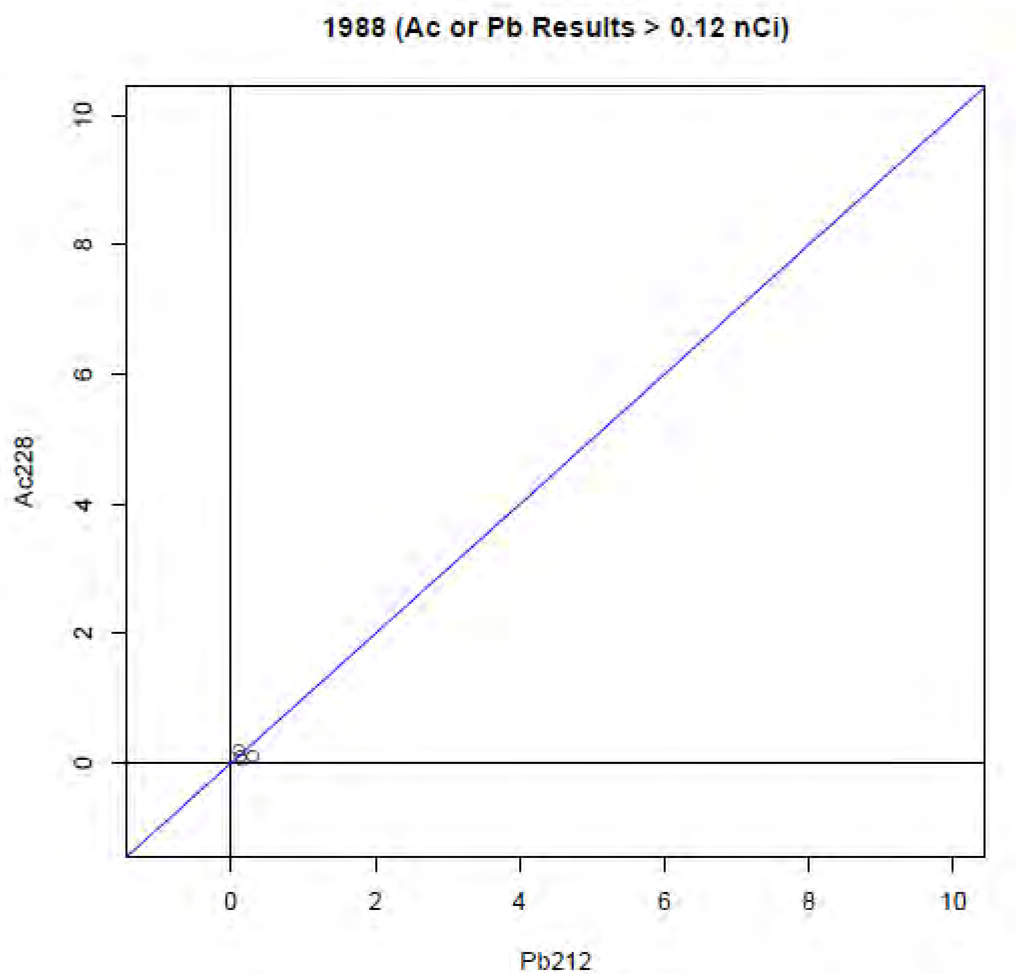

1987 (Ac and Pb Results > 0.12 nCi)
Ac228
Pb212
−0.2
0.0
0.2
0.4
0.6
0.8
1.0

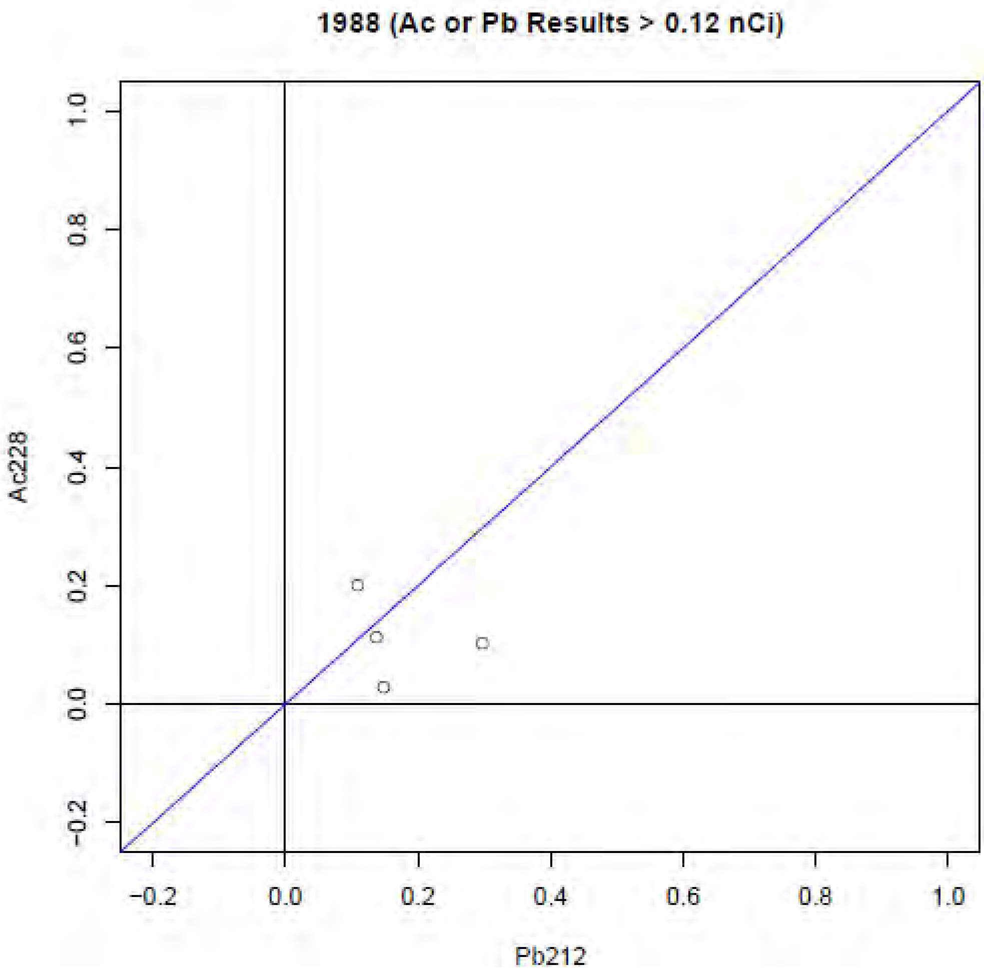

1987 (Ac or Pb Results > 0.12 nCi)
Ac228
Pb212
0
2
4
6
8
10


1987 (Ac or Pb Results > 0.12 nCi)
Ac228
Pb212
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.2 0.0 0.2 0.4 0.6 0.8 1.0


1988 (Ac and Pb Results > 0.12 nCi)
Ac228
Pb212
0
2
4
6
8
10
0
2
4
6
8
10


1988 (Ac and Pb Results > 0.12 nCi)
Ac228
Pb212
-0.2
0.0
0.2
0.4
0.6
0.8
1.0


1988 (Ac or Pb Results > 0.12 nCi)
Ac228
Pb212
0
2
4
6
8
10


1988 (Ac or Pb Results > 0.12 nCi)
Ac228
Pb212
−0.2
0.0
0.2
0.4
0.6
0.8
1.0

ATTACHMENT B-2

Activity Ratios for Various Types of Thorium

Tom LaBone
June 21, 2013

In an April 18, 2013 white paper entitled *Evaluation of Fernald Ac-228/Pb-212 Chest Count Data* I recommended that chest counts with a high Ac-228 : Pb-212 ratio (greater than 1.5 : 1) be interpreted as intakes of a mixture of triple-separated thorium and unsupported Ra-228. During the Fernald working group call on June 17, it was suggested that we should instead interpret these chest counts as being the result of intakes of some form of freshly separated thorium. I have looked at this issue for a while now and I am unable to identify a form of separated thorium likely to be encountered at Fernald that would explain the observed high Ac-228 : Pb-212 ratios. The following discussion documents my calculations.

The decay scheme of Th-232 down to Pb-212 is shown below:

$$^{232}Th \xrightarrow{1.405\times10^{10}\,y} {}^{228}Ra \xrightarrow{5.75\,y} {}^{228}Ac \xrightarrow{6.13\,h} {}^{228}Th$$

$$^{228}Th \xrightarrow{1.91\,y} {}^{224}Ra \xrightarrow{3.62\,d} {}^{220}Rn \xrightarrow{55.6\,s} {}^{216}Po \xrightarrow{0.146\,s} {}^{212}Pb \xrightarrow{10.6\,h}$$

The radionuclides of interest, i.e., those that can be quantified with a chest count, are the Ac-228 and the Pb-212.

A chemical separation or stripping of the thorium will remove all non-thorium elements. Immediately after separation, the daughters of Th-232 and Th-228 will start to grow in. A cursory examination of the half-lives of the members of this decay chain reveals that:

- A few weeks after separation, the Pb-212 present is equal to the amount of Th-228 that is present.
- A couple of days after separation, the Ac-228 present is equal to the amount of Ra-228 that is present.

It is important to note that when separations are performed the Ac-228 present is not necessarily related to the amount of Th-232 present because the Ra-228 has a half-life long enough to permit its presence in the workplace independent of its parent Th-232. On the other hand, if Pb-212 is observed then there must necessarily be Th-228 present, and if there is Th-228 present then there must be Th-232 present (although not in equal quantities). This is why we chose to evaluate the Pb-212 chest count data rather than the Ac-228 chest count data.

We are interested in the Ac-228 : Pb-212 ratios that might be encountered in chest counts performed on workers following exposure to thorium in the workplace. The thorium mixtures[4] examined here are:

- *Single-Sep Thorium* is Th-232 in equilibrium with all of its daughters that is then stripped of the non-thorium daughters. Immediately after the stripping procedure is completed, all that remains are Th-232 and Th-228 in a 1 : 1 activity ratio.
- *Double-Sep Thorium* is Single-Sep Thorium that is aged 4.55 years and then stripped of the non-thorium daughters. Immediately after the stripping procedure is completed, all that remains are Th-232 and Th-228 in a 1 : 0.422 activity ratio.
- *Triple-Sep Thorium* is Double-Sep Thorium that is aged 2.536 years and then stripped of the non-thorium daughters. Immediately after the stripping procedure is completed, all that remains are Th-232 and Th-228 in a 1 : 0.263 activity ratio.
- *Enriched Thorium* has a Th-232 : Th-228 activity ratio of 1 : 0.0006. This material is essentially pure Th-232 by activity and could only be produced by some sort of intentional enrichment process.
- *Dirty Thorium* is thorium that is separated from the radium with a 10 : 1 decontamination factor. Thus, immediately after the separation procedure the Th-232 : Ra-228: Th-228 : Ra-224 ratios are 1 : 0.1 : 1 : 0.1.

The first five plots show the quantity of Ac-228 and Pb-212 present in the chest following acute inhalation intakes of each of the five types of thorium described above, each being 5 µm AMAD Type S aerosols. On the sixth plot the Ac-228 : Pb-212 ratio for all five materials are presented. These plots were constructed from intake retention fractions generated with DCAL, which accurately implements the independent biokinetics of the thorium chain.

The pink dashed line on the sixth plot shows a 20 : 1 ratio, which is a ratio that has been observed in an actual chest count of a worker at Fernald. This plot demonstrates that a 20 : 1 ratio would be observed only in the cases where something exotic like Enriched Thorium is inhaled, or if unsupported Ra-228 is inhaled along with a more realistic form of thorium[5]. I consider the latter explanation to be the only plausible one at Fernald.

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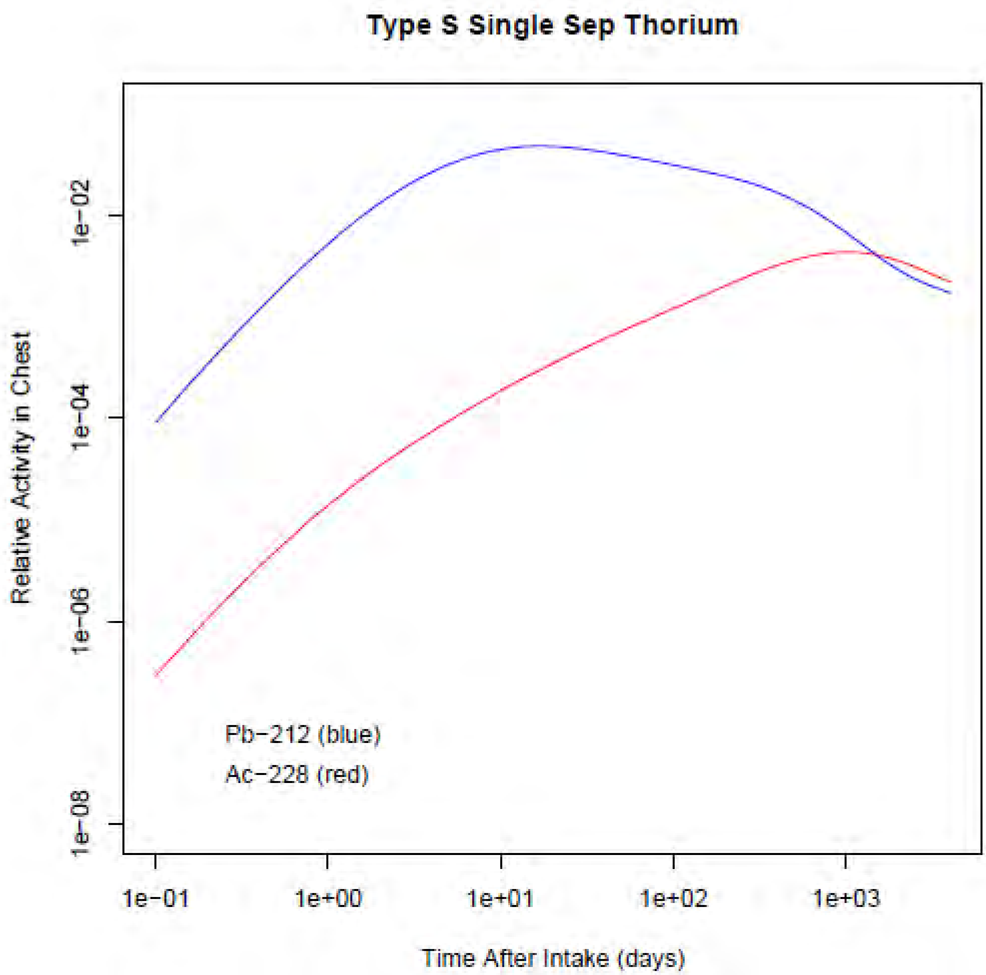
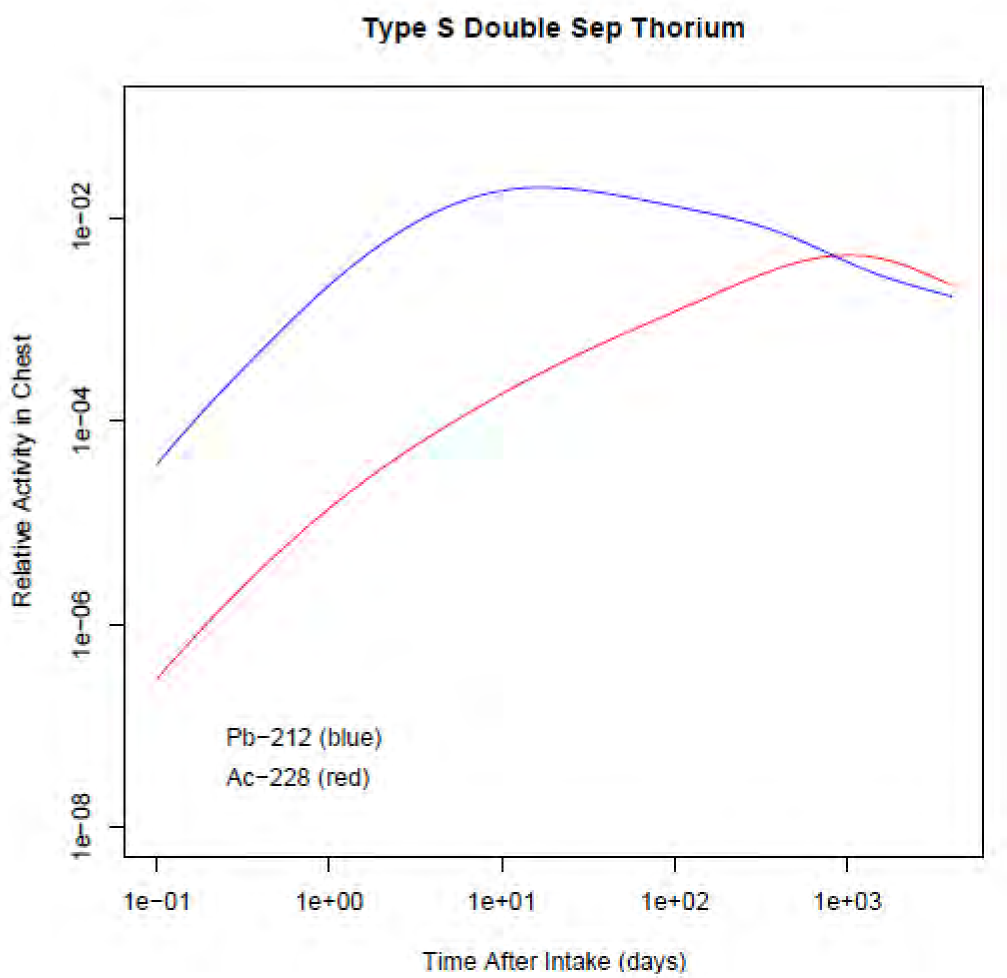
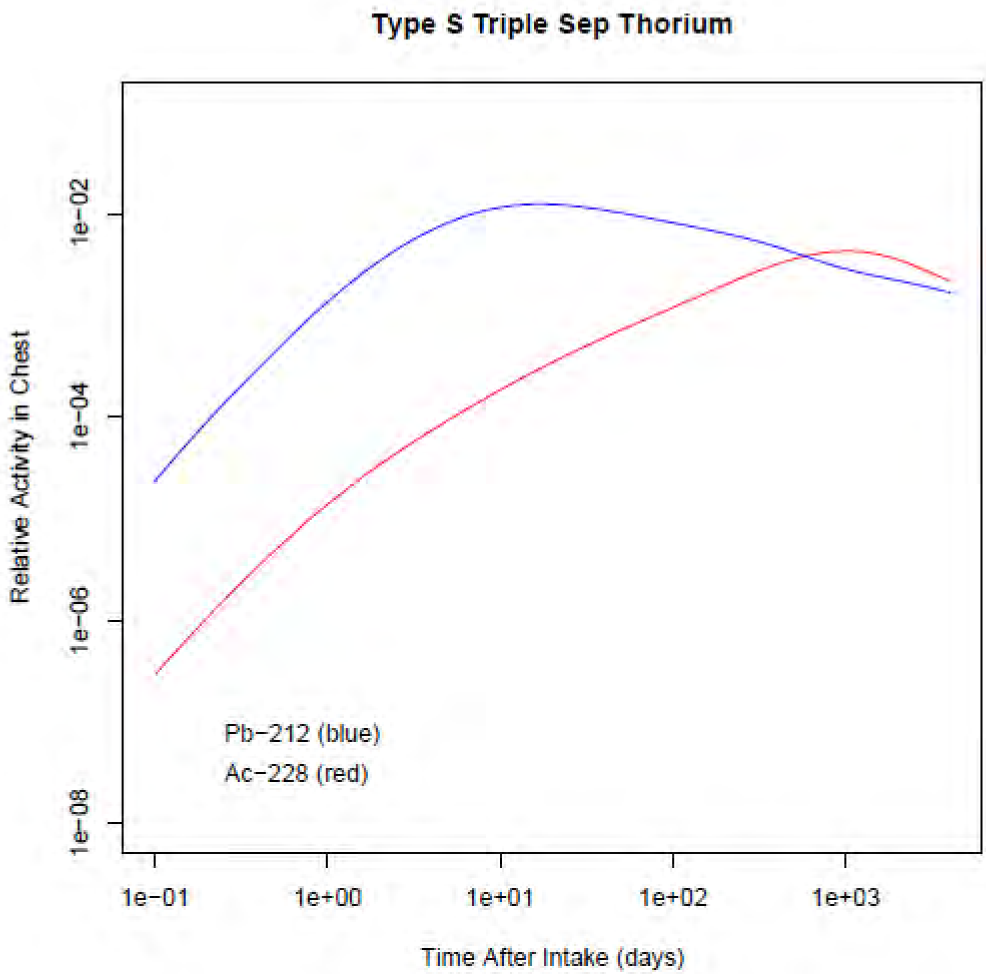
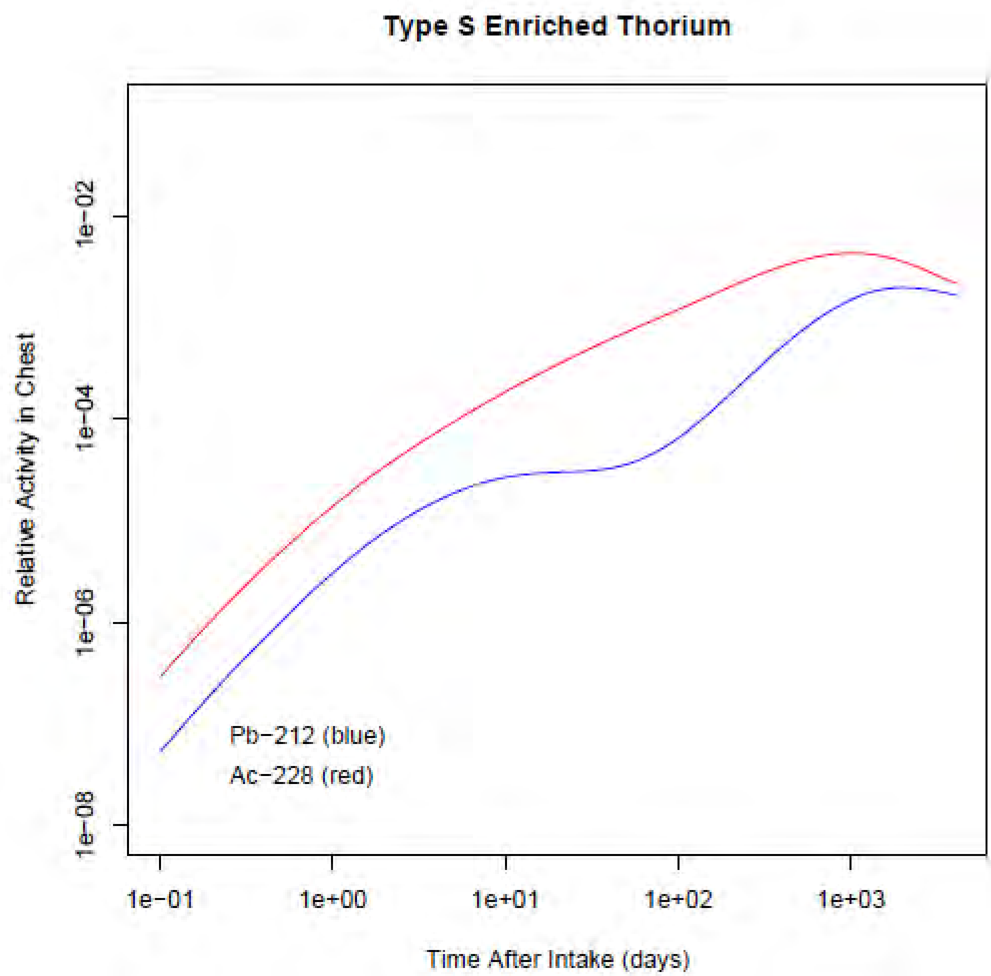
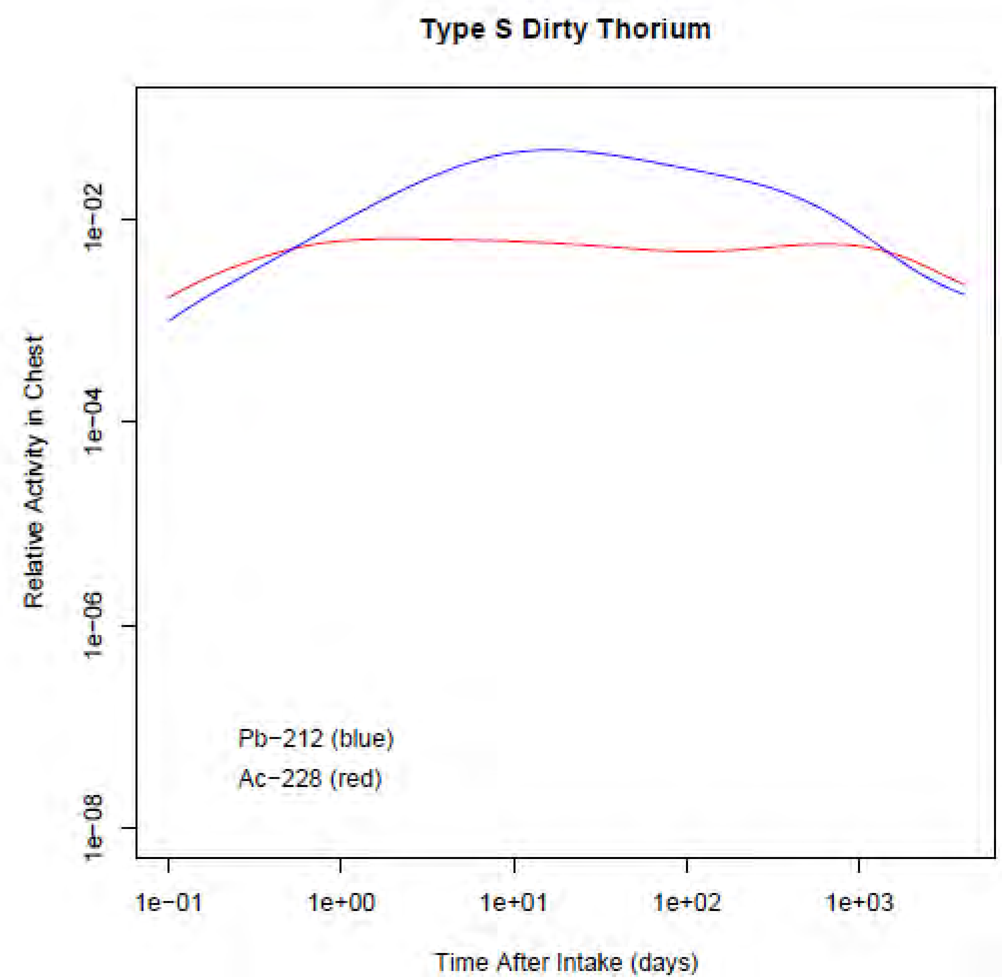
[4] Note that Single-Sep, Double-Sep, and Triple-Sep Thorium are defined differently than in previous technical papers because we are interested in the composition of the material immediately after separation.
[5] The same conclusions are reached with Type M material and for whole-body counts.

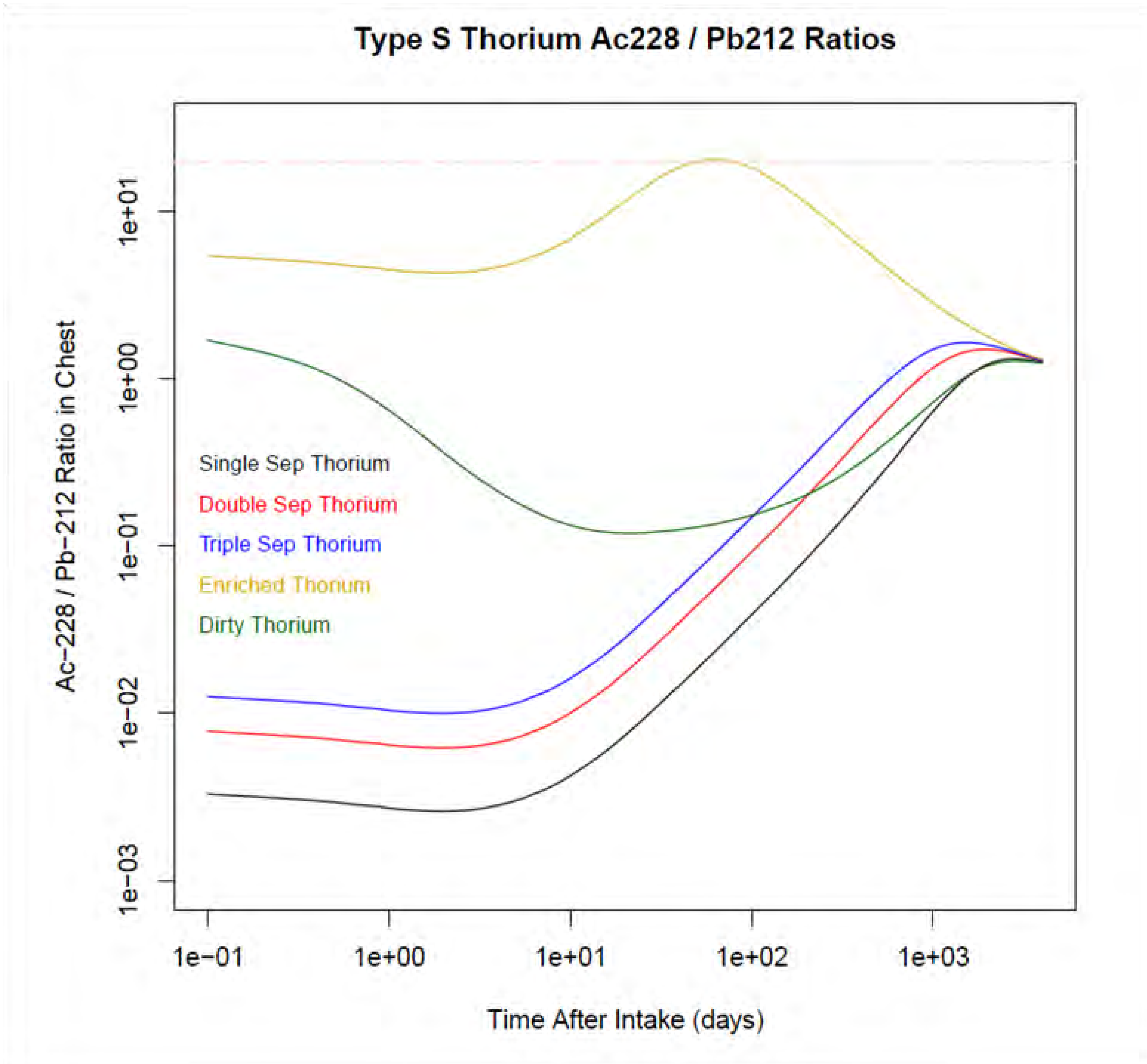

Type S Single Sep Thorium
Relative Activity in Chest
1e−02
1e−04
1e−06
1e−08
1e−01
1e+00
1e+01
1e+02
1e+03
Time After Intake (days)
Pb−212 (blue)
Ac−228 (red)


Type S Double Sep Thorium
Relative Activity in Chest
1e−02
1e−04
1e−06
1e−08
Pb−212 (blue)
Ac−228 (red)
1e−01
1e+00
1e+01
1e+02
1e+03
Time After Intake (days)


Type S Triple Sep Thorium
Relative Activity in Chest
1e−02
1e−04
1e−06
1e−08
Pb−212 (blue)
Ac−228 (red)
1e−01
1e+00
1e+01
1e+02
1e+03
Time After Intake (days)


Type S Enriched Thorium
Relative Activity in Chest
1e−02
1e−04
1e−06
1e−08
Pb−212 (blue)
Ac−228 (red)
1e−01
1e+00
1e+01
1e+02
1e+03
Time After Intake (days)


Type S Dirty Thorium
Relative Activity in Chest
1e−02
1e−04
1e−06
1e−08
Pb−212 (blue)
Ac−228 (red)
1e−01
1e+00
1e+01
1e+02
1e+03
Time After Intake (days)


Type S Thorium Ac228 / Pb212 Ratios
Ac−228 / Pb−212 Ratio in Chest
1e−03
1e−02
1e−01
1e+00
1e+01
Single Sep Thorium
Double Sep Thorium
Triple Sep Thorium
Enriched Thorium
Dirty Thorium
1e−01
1e+00
1e+01
1e+02
1e+03
Time After Intake (days)

ATTACHMENT B-3

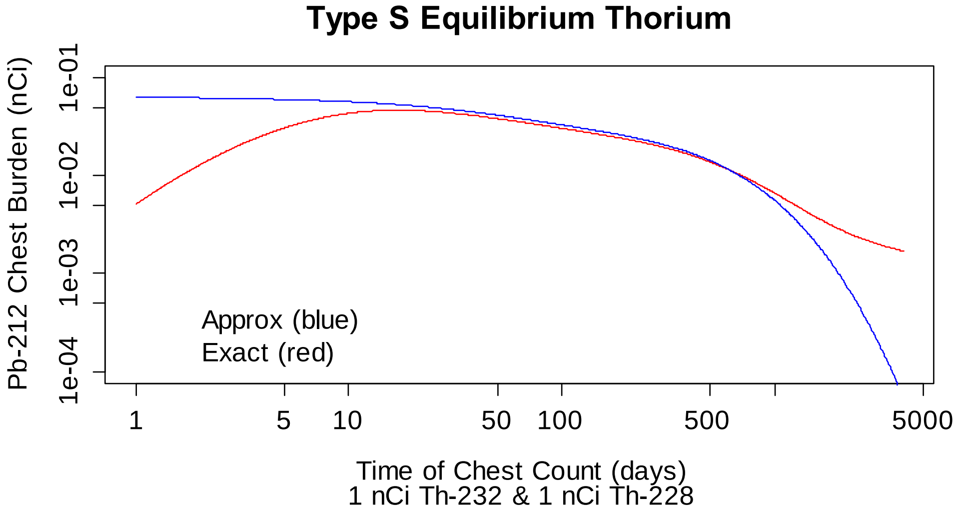
Approximate Evaluation of Pb-212 Chests Counts Following Intakes of Thorium
Tom LaBone
July 19, 2013

In this paper I suggest ways to adjust intakes and intake rates of Th-232 and Th-228 calculated from Pb-212 chest burdens with IMBA so that the intakes and intake rates will not underestimate those calculated with exact methods (DCAL). These adjustments may be used when an overestimate of dose is appropriate. Best estimates of dose require the use of DCAL.

Acute Intakes

Assume a mixture of 1 nCi of Th-232 and 1 nCi of Th-228 (both being 5 µm AMAD Type S material) was inhaled. The Pb-212 chest burden as a function of time after the acute intake is shown in Figure 1 below.

Figure 1. Pb-212 chest burden following an acute inhalation intake of Type S thorium having a Th-228 to Th-232 ratio of 1 : 1.



The exact chest burden *q* of Pb-212 at *t* days after an acute inhalation intake is given by

$$q(t) = q_{pbth232}(t) + q_{pbth228}(t),$$

where *qpbth232* is the chest burden of Pb-212 that grows in from the inhaled Th-232 and *qpbth228* is the chest burden of Pb-212 that grows in from the inhaled Th-228. These exact burdens are calculated with DCAL, which accounts for independent kinetics of the thorium decay chain and the loss of Rn-220. Two approximations can be made here:

- The amount of Pb-212 present equals the amount of Th-228 present at all times after the intake, i.e.,

$$q(t) = q_{pbth232}(t) + q_{pbth228}(t),$$

- There is negligible ingrowth of Pb-212 from the Th-232 component of the intake, i.e.,

$$q_{pbth232}(t) = 0 .$$

This gives the following approximation to *q*:

$$q'(t) = q_{th228}(t),$$

where *qth228* is the Th-228 chest burden at time *t* (which can be calculated with IMBA). As seen in the plot above, these approximations provide reasonably accurate estimates of the Pb-212 burden between approximately10 and 1000 days after the intake.

For example, assume that a Pb-212 chest burden of 1.5 nCi is observed at 100 days after an acute inhalation intake of this Type S thorium. The intake of Th-232 is

$$I = \frac{1.5\,nCi}{q_{pbth232}(100) + q_{pbth228}(100)}.$$

$$I = \frac{1.5\,nCi}{4.64\times10^{-5} + 0.0306} = 48.95\,nCi,$$

which translates into 48.95 nCi of Th-228. These intakes can be checked by calculating the expected Pb-212 chest burden and seeing if it equals the burden from which the intakes were calculated:

$$1.5\,nCi = (48.95\,nCi)(4.64\times10^{-5}) + (48.95\,nCi)(0.0306).$$

With the approximate method we have a Th-228 intake of

$$I = \frac{1.5\,nCi}{q_{th\,228}\left(100\right)}.$$

$$I = \frac{1.5\,nCi}{0.0332} = 45.18\,nCi.$$

which translates into a 45.18 nCi intake of Th-232.

In this discussion I present plots of Pb-212 chest burdens calculated with the exact and approximate methods given thorium intakes. I find these plots to be intuitive and easier to interpret than other types of plots. Note that in this example

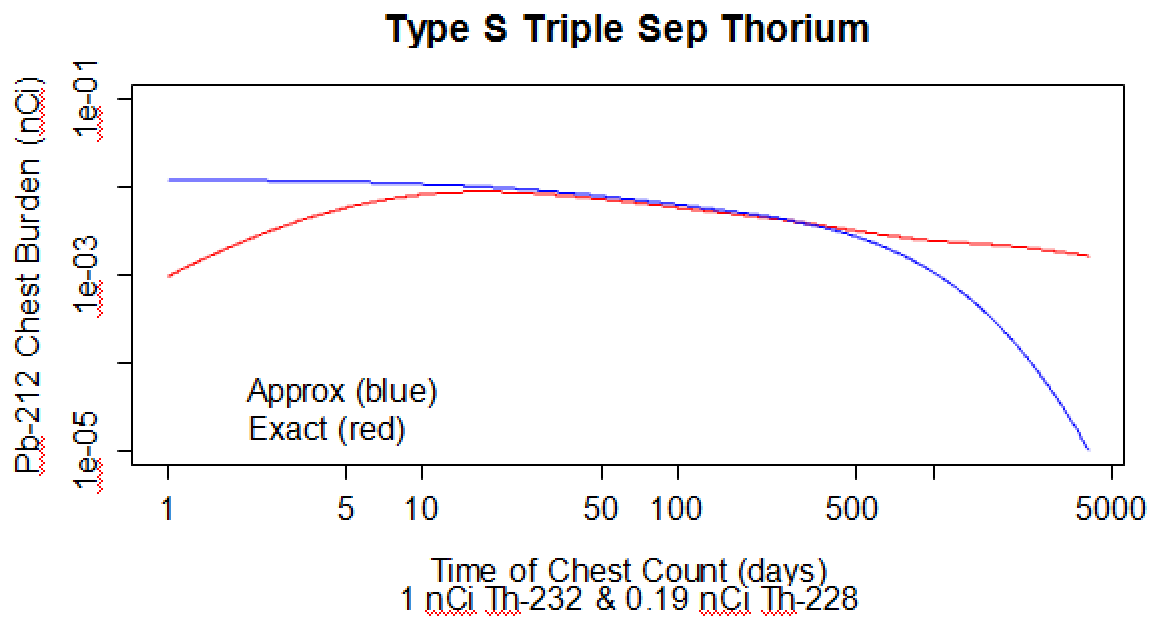
- for a given <u>intake</u> the exact method gives a lower <u>chest burden</u> than does the approximate method at t = 100 days (see the plot above), but
- for a given <u>chest burden</u> the exact method gives a larger <u>intake</u> than does the approximate method.

In practice we will typically calculate intakes from chest burdens. Thus, the plot in Figure 1 can be interpreted to mean that the approximate method will underestimate intakes at times prior to ~300 days after the intake (where the curves cross) and overestimate intakes after that day.

Triple Separated Thorium Mixture

Now assume a mixture of 1 nCi of Th-232 and 0.19 nCi of Th-228 (both being 5 µm AMAD Type S material) was inhaled. The Pb-212 chest burden as a function of time after the acute intake is shown in Figure 2 below. Thorium with a Th-228 : Th-232 ratio of 0.19 : 1 is referred to as *Triple Separated Thorium*.

Figure 2. Pb-212 chest burden following an acute inhalation intake of Type S thorium having a Th-228 to Th-232 ratio of 0.19 : 1.



The exact chest burden *q* of Pb-212 at *t* days after an acute inhalation intake is given by

$$q(t) = q_{pbth232}(t) + 0.19 q_{pbth228}(t).$$

Applying the two approximations gives the following approximation to *q*:

$$q'(t) = q_{th228}(t).$$

For example, assume that a Pb-212 chest burden of 1.5 nCi is observed at 100 days after an acute inhalation intake of this Type S thorium. The intake of Th-232 is

$$I = \frac{1.5\,nCi}{q_{pbth232}(100) + 0.19 q_{pbth228}(100)}.$$

$$I = \frac{1.5\,nCi}{4.64 \times 10^{-5} + (0.19)(0.0306)} = 255.96\,nCi,$$

which translates into (0.19)(255.96 nCi) = 48.63 nCi of Th-228. As a check, it is useful to show that

$$1.5\,nCi = (255.96\,nCi)(4.64\times10^{-5}) + (48.63\,nCi)(0.0306).$$

With the approximate method the intake of Th-228 is

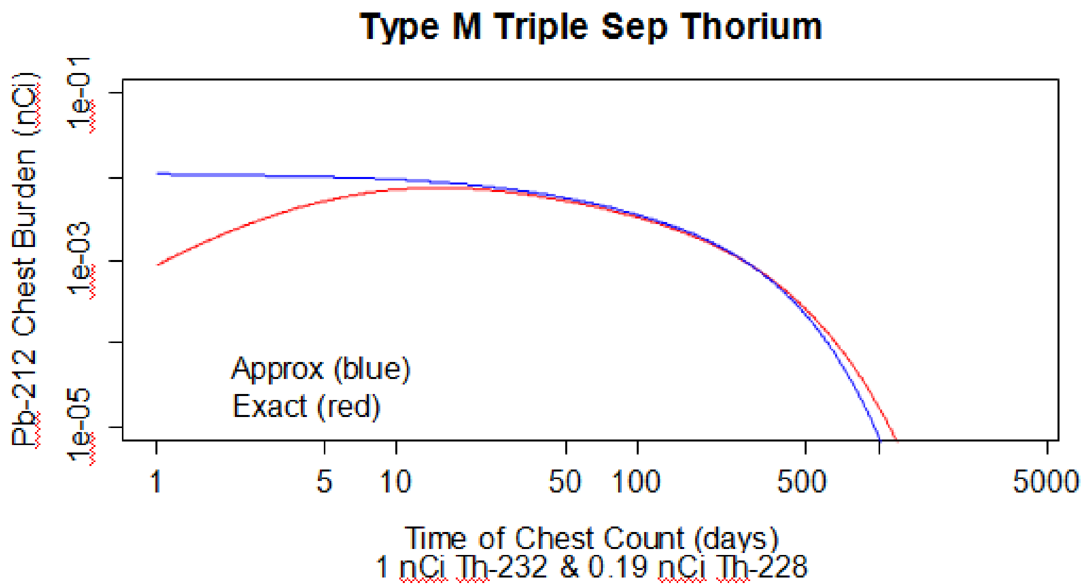
$$I = \frac{1.5\,nCi}{q_{th\,228}(100)}.$$

$$I = \frac{1.5\,nCi}{0.0332} = 45.18\,nCi.$$

which gives (45.18 nCi) / (0.19) = 237.79 nCi of Th-232.

The plot for Type M triple separated thorium is shown below. Other than the fact that there is faster clearance of the thorium from the chest, all of the discussion above is directly applicable to Type M material.

Figure 3. Pb-212 chest burden following an acute inhalation intake of Type M thorium having a Th-228 to Th-232 ratio of 0.19 : 1.



Adjustment of Thorium Intakes

As shown in the plots above, for a given thorium intake, the approximate method will overestimate the Pb-212 chest burden for a length of time after the intake (~2 years for Type S material). Thus, for a given Pb-212 chest burden, the approximate method will underestimate the thorium intake for the same length of time. In Figures 4 and 5, an adjustment factor of 1/1.1 is applied to the approximate Pb-212 chest burdens to ensure that they do not overestimate the exact Pb-212 chest burdens at times greater than 30 days post intake.

Figure 4. Pb-212 chest burden following an acute inhalation intake of Type S thorium having a Th-228 to Th-232 ratio of 0.19 : 1. The vertical dashed line is at t = 30 days post intake.

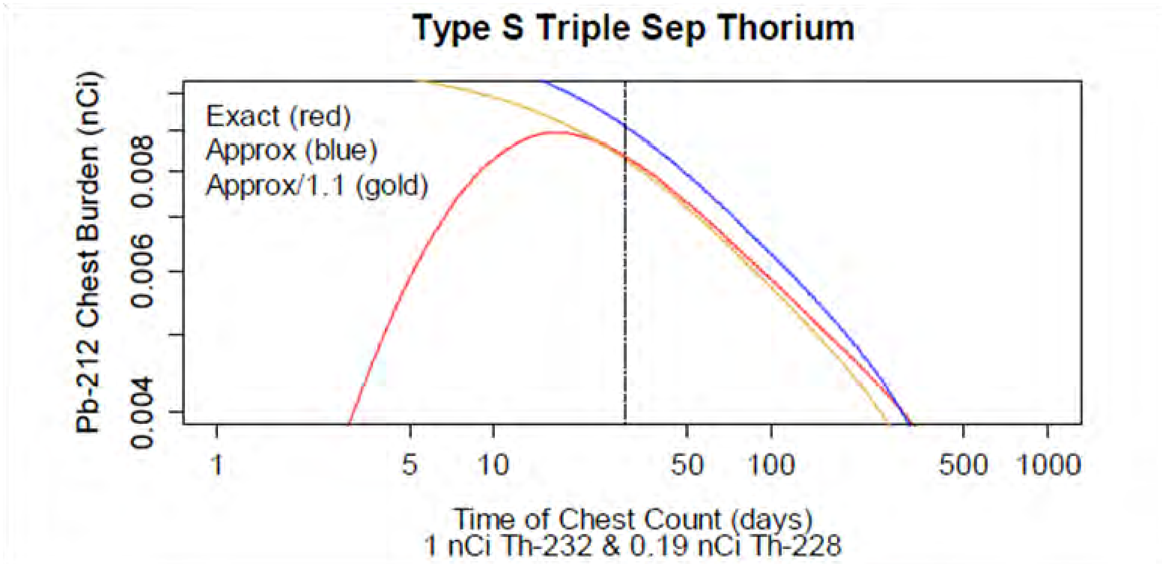
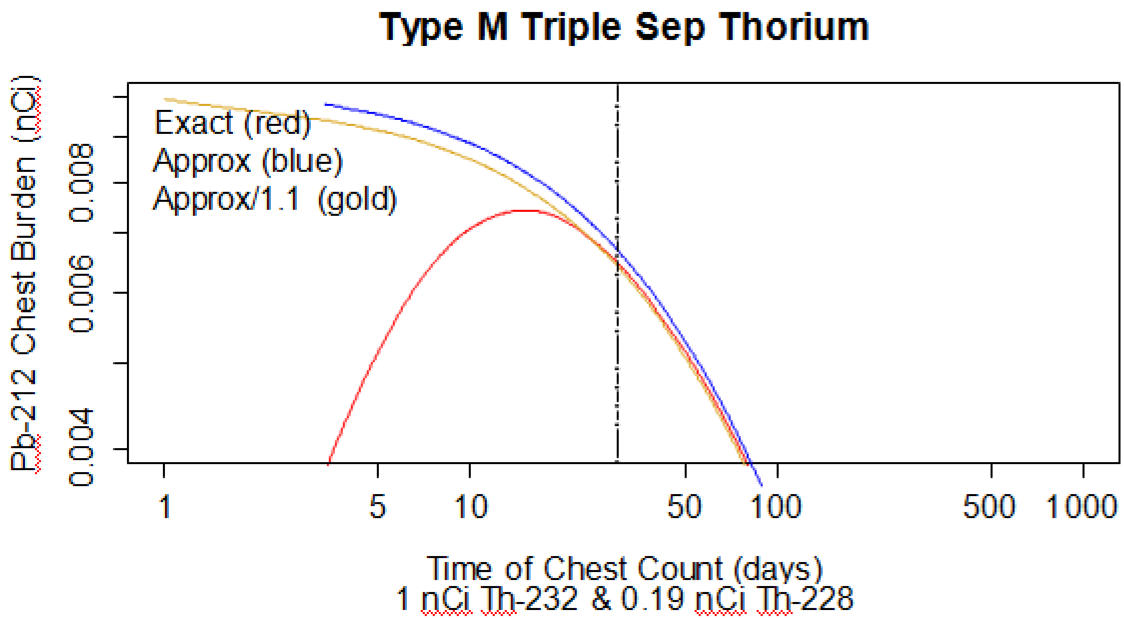


Figure 5. Pb-212 chest burden following an acute inhalation intake of Type M thorium having a Th-228 to Th-232 ratio of 0.19 : 1. The vertical dashed line is at t = 30 days post intake.



When using the approximate method to calculate thorium intakes from Pb-212 chest burdens, the intake is multiplied by an adjustment factor of 1.1 to achieve the desired end of not underestimating the intake that would have been calculated using the exact method.

Guidance for Acute Intakes

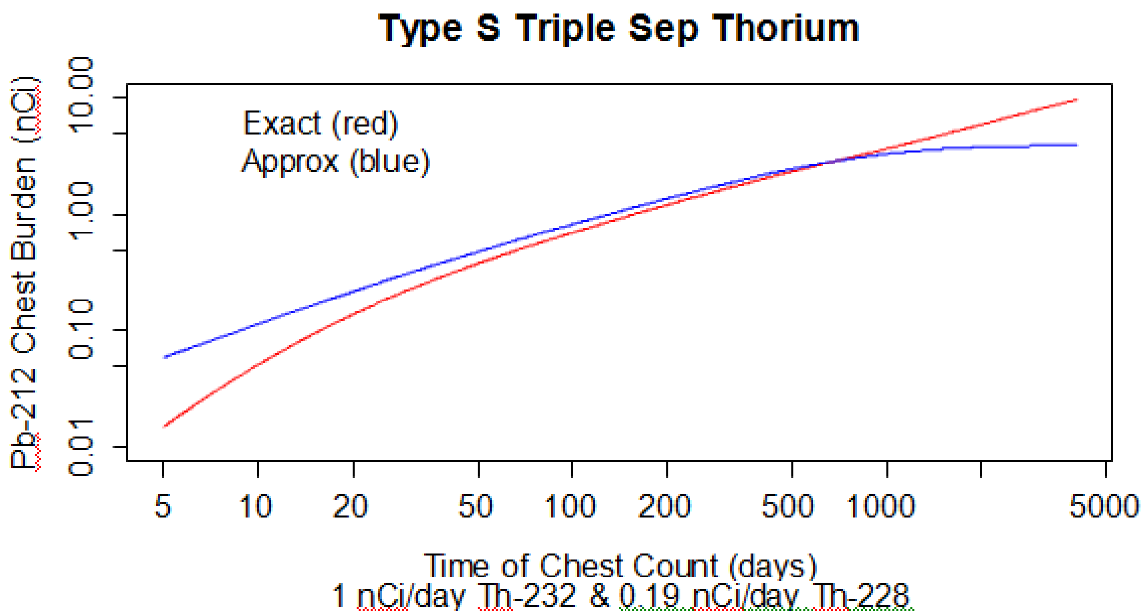
Based on discussion given above, the following guidance is offered on how to use the approximate method to evaluate Pb-212 chest count data following acute inhalation intakes of Type M or S thorium:

Assume we have a single measured Pb-212 chest burden. Evaluate the chest burden with a Th-228 biokinetic model in IMBA. Multiply the calculated Th-228 intake by a factor of
1.1 and assign it as the intake of Th-228. Divide this estimated Th-228 intake by the Th-228 : Th-232 ratio of 0.19 : 1 to obtain the Th-232 intake. For Pb-212 chest burdens measured more than 30 days after an acute intake, these approximate intakes will not underestimate the intakes calculated with exact methods.

Chronic Intakes

The plot in Figure 4 below shows the Pb-212 chest burden as a function of time following a chronic intake of 1 nCi/day of Th-232 and 0.19 nCi/day of Th-228 (both being 5 µm AMAD Type S material). In other words, the time on the abscissa is the length of the time after the start of the chronic intake and the time that the chest burden is determined. The two curves cross at ~700 days.

Figure 6. Pb-212 chest burden following a chronic inhalation intake of Type S thorium having a Th-228 to Th-232 ratio of 0.19 : 1.



The equations for chronic intakes are essentially the same as in the case of acute intakes except that the functions have an argument for the length of the constant chronic intake period. The exact chest burden *q* of Pb-212 at *t* days after the start of a t_C day chronic inhalation intake is given by

$$q\left(t,t_c\right)=q_{pbth232}\left(t,t_c\right)+0.19q_{pbth228}\left(t,t_c\right) \qquad t\geq t_c\,.$$

Applying the two approximations gives the following approximation to *q*:

$$q'\left(t,t_c\right)=q_{th228}\left(t,t_c\right),$$

For example, assume that a Pb-212 chest burden of 1.5 nCi is observed at the end of a 365-day chronic inhalation intake of Type S triple separated thorium. The total intake of Th-232 is

$$I = \frac{1.5\,nCi}{q_{pbth232}(365,365) + 0.19 q_{pbth228}(365,365)}.$$

$$I = \frac{1.5\,nCi}{1.641\times 10^{-4} + (0.19)(0.02654)} = 288.1\,nCi,$$

which translates into (0.19)(288.1 nCi) = 54.74 nCi of Th-228. This can be seen by rearranging the above equation:

$$1.5\,nCi = (288.1\,nCi)(1.641\times 10^{-4}) + (54.74\,nCi)(0.02654).$$

The intake rates are obtained by dividing the intakes by t_C = 365 days. With the approximate method the intake of Th-228 is

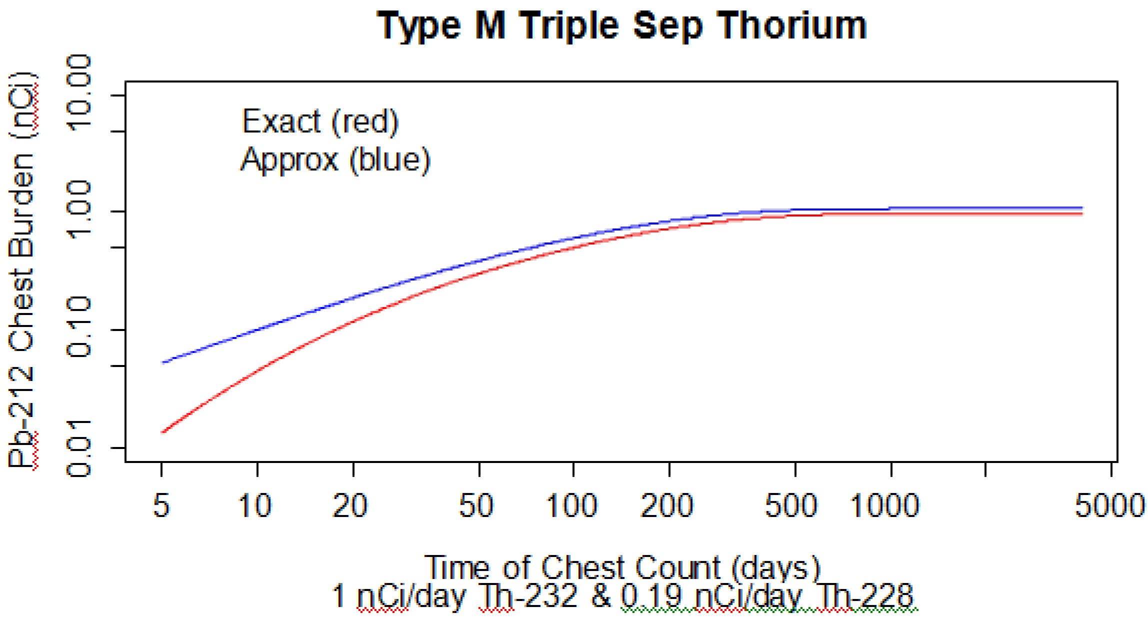
$$I = \frac{1.5\,nCi}{q_{th228}(365,365)}.$$

$$I = \frac{1.5\,nCi}{(0.02980)} = 50.34\,nCi,$$

which gives (50.34 nCi) / (0.19) = 264.9 nCi of Th-232.

The plot for Type M triple separated thorium is shown in Figure 5 below. After a few hundred days the Pb-212 chest burden achieves a steady state condition with the approximate method giving a chest burden ~10% higher than the exact method.

Figure 7. Pb-212 chest burden following a chronic inhalation intake of Type M thorium having a Th-228 to Th-232 ratio of 0.19 : 1.



Adjustment of Chronic Thorium Intakes

In Figures 8-13, the Pb-212 chest burdens at various times during and after 365 day, 1000 day, and 5000 day constant chronic intakes are presented. As was done with the acute intakes, the approximate Pb-212 chest burdens are adjusted by a factor of 1/1.1. This illustrates that intake rates calculated from Pb-212 chest counts with the approximate method can be adjusted by a factor of 1.1 to ensure that the intake rates do not underestimate the intake rates calculated with the exact method.

Figure 8. Pb-212 chest burden during and following a 365-day chronic inhalation intake of Type S thorium having a Th-228 to Th-232 ratio of 0.19 : 1. The vertical dashed line is at t = 365 days.

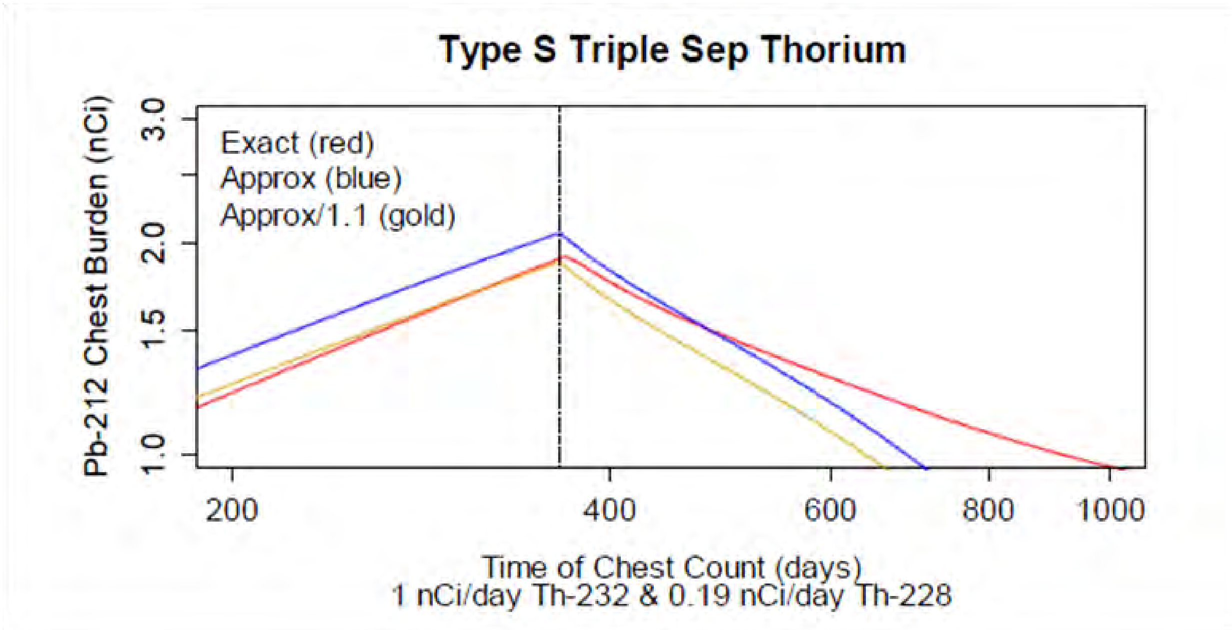


Figure 9. Pb-212 chest burden during and following a 1000-day chronic inhalation intake of Type S thorium having a Th-228 to Th-232 ratio of 0.19 : 1. The vertical dashed line is at t = 1000 days.

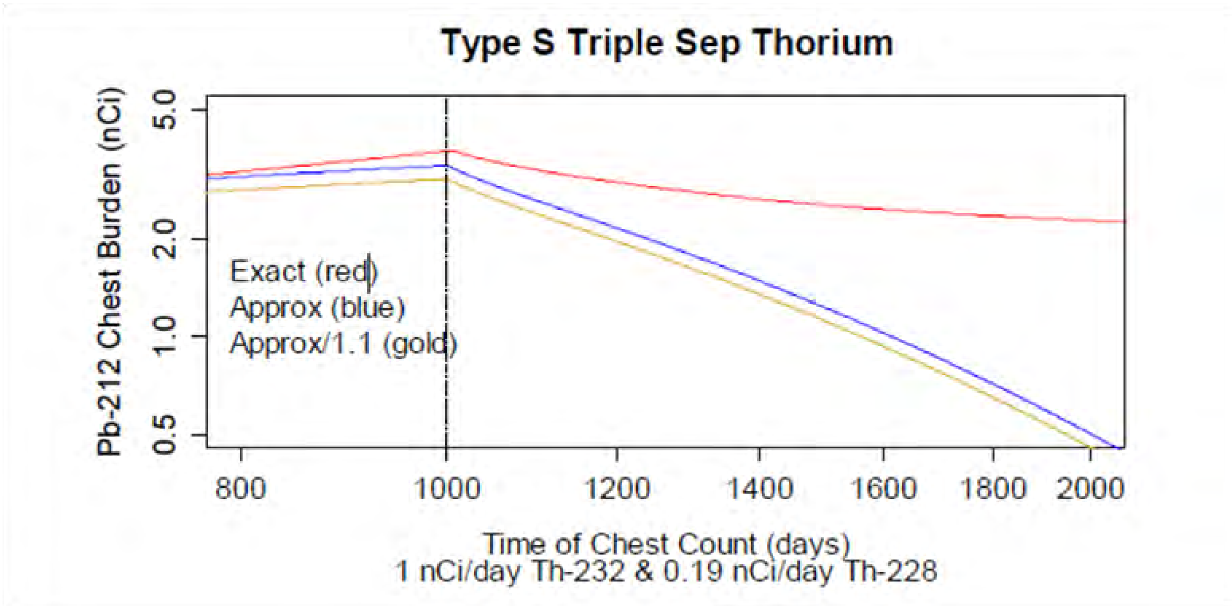


Figure 10. Pb-212 chest burden during and following a 5000-day chronic inhalation intake of Type S thorium having a Th-228 to Th-232 ratio of 0.19 : 1. The vertical dashed line is at t = 5000 days.

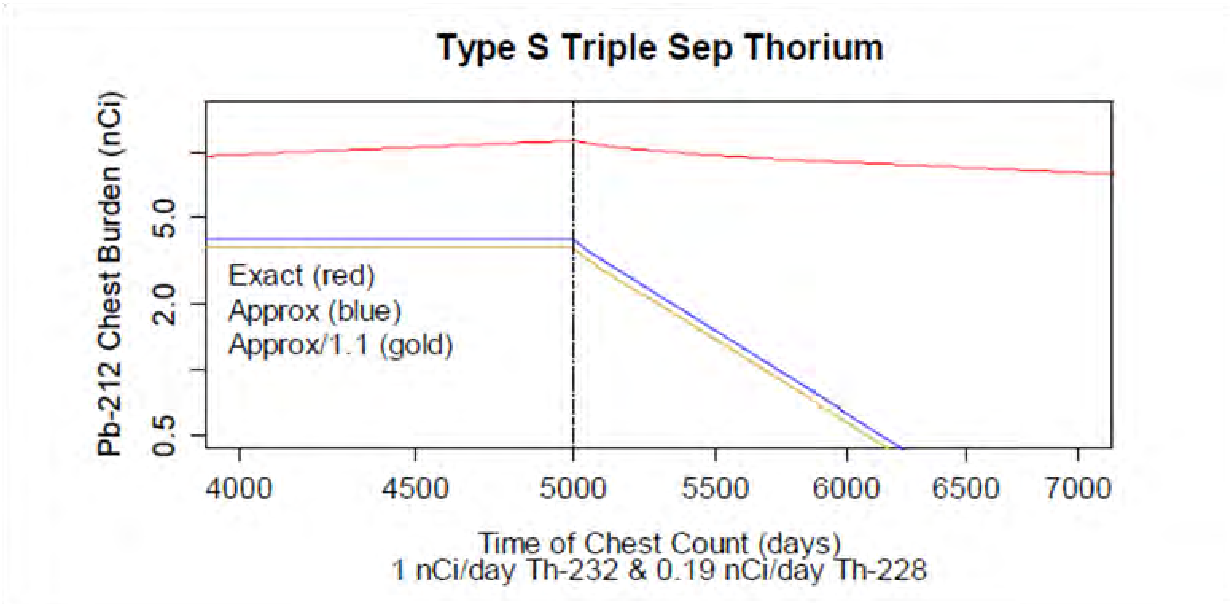


Figure 11. Pb-212 chest burden during and following a 365-day chronic inhalation intake of Type M thorium having a Th-228 to Th-232 ratio of 0.19 : 1. The vertical dashed line is at t = 365 days.

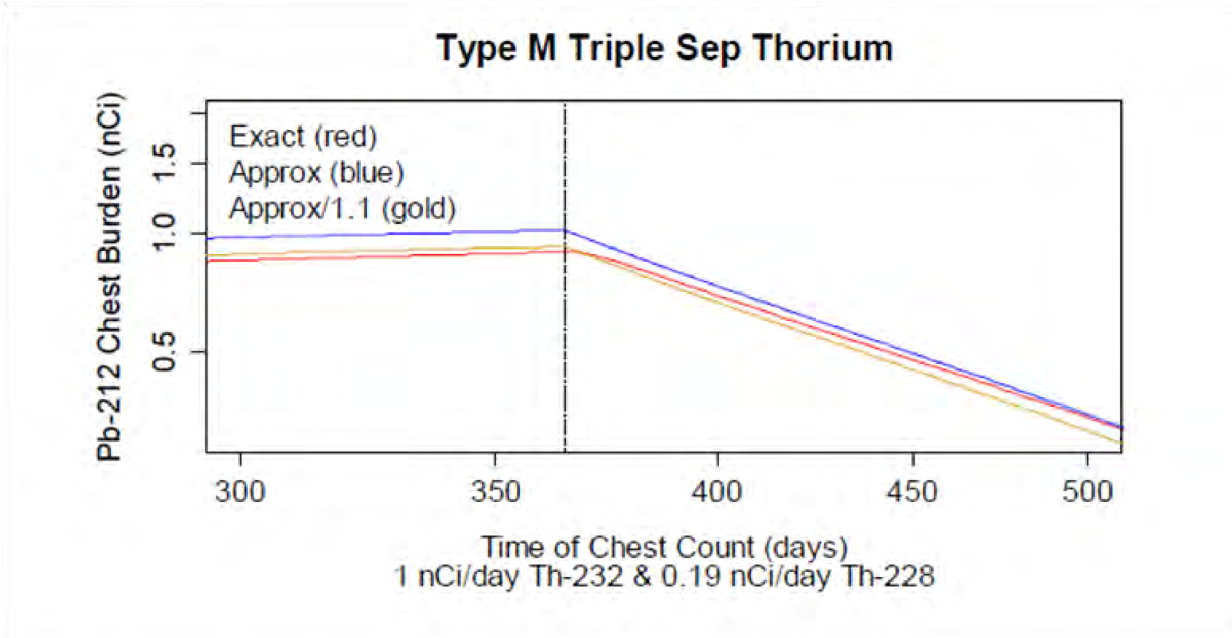


Figure 12. Pb-212 chest burden during and following a 1000-day chronic inhalation intake of Type M thorium having a Th-228 to Th-232 ratio of 0.19 : 1. The vertical dashed line is at t = 1000 days.

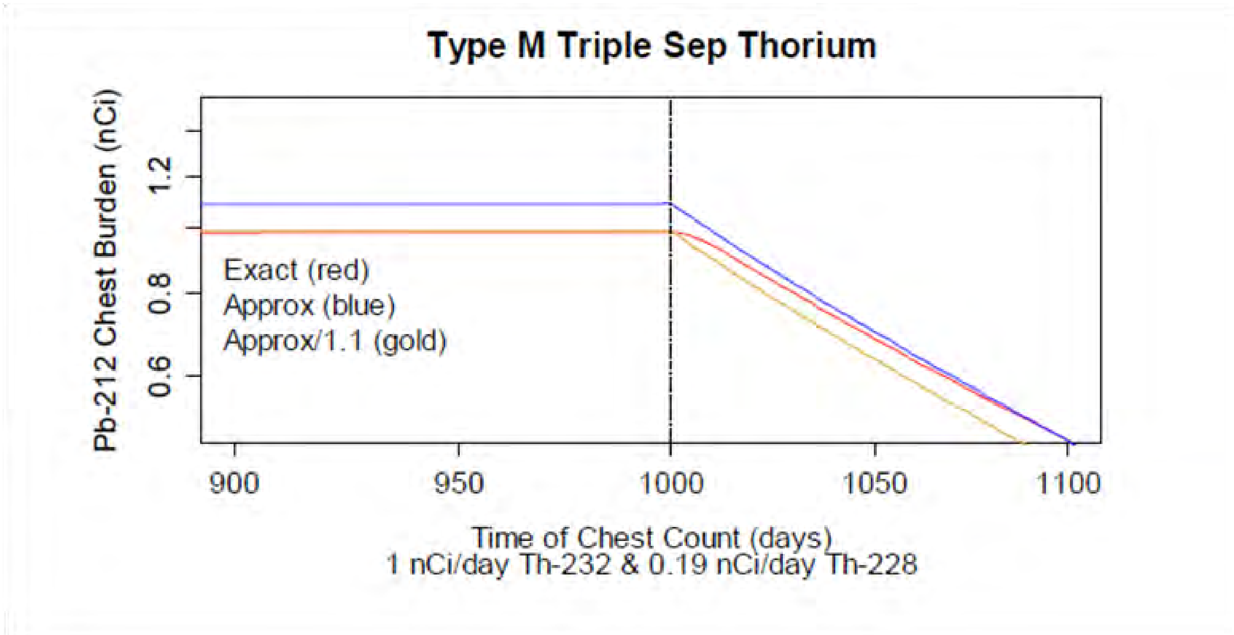
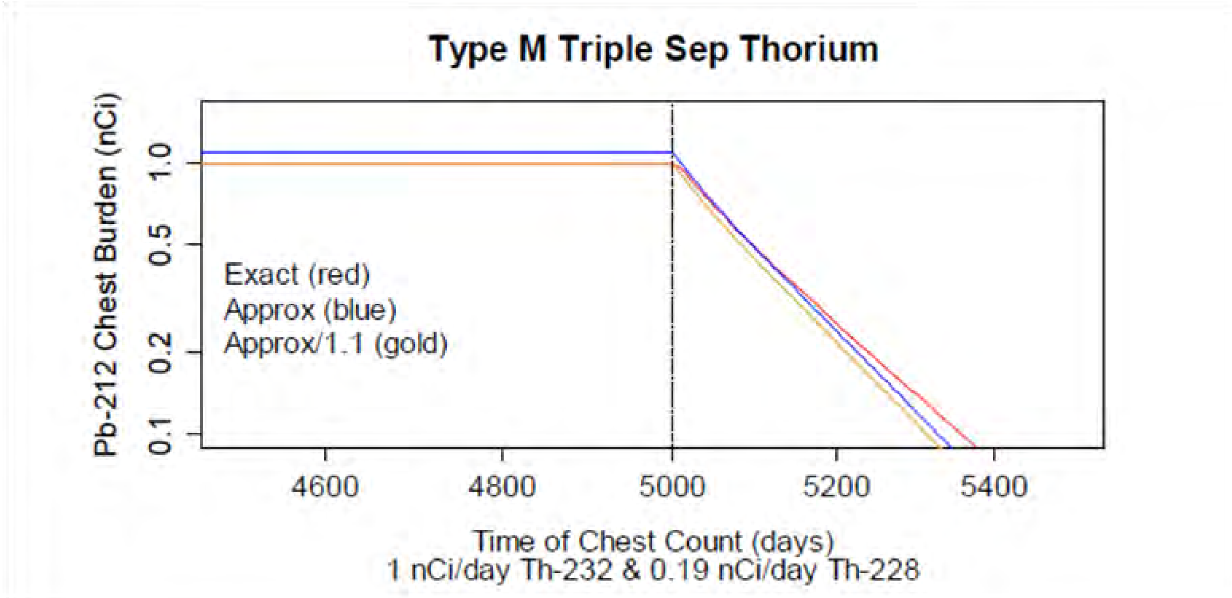


Figure 13. Pb-212 chest burden during and following a 5000-day chronic inhalation intake of Type M thorium having a Th-228 to Th-232 ratio of 0.19 : 1. The vertical dashed line is at t = 5000 days.



Guidance for Chronic Intakes

Based on discussion given above, the following guidance is offered on how to use the approximate method to evaluate Pb-212 chest count data following constant chronic inhalation intakes of triple separated thorium:

Assume we have a single measured Pb-212 chest burden. Evaluate the chest burden with a Th-228 biokinetic model in IMBA. Multiply the calculated Th-228 intake rate by a factor of 1.1 and assign it as the intake rate of Th-228. Divide this estimated Th-228 intake rate by the Th-228 : Th-232 ratio of 0.19 : 1 to obtain the Th-232 intake rate. For chronic intakes longer than 1 year these approximate intakes will not underestimate the intakes calculated with exact methods.

ATTACHMENT B-4

Using Ac-228 and Pb-212 to Measure Intakes of Th-232

Tom LaBone
September 18, 2013

Introduction

The following four reports issued over the past 18 months present the technical basis for using Pb-212 measured chest burdens to calculate inhalation intakes of Th-232 at Fernald and at other facilities where thorium was chemically processed:

> *Calculation of Chronic Intake IRFs for Th-232 Assuming Independent Kinetics*, February 17, 2012. In this paper we present the theoretical basis for calculating intake retention fractions that account for independent biokinetics of the Th-232 decay chain. In other words, we demonstrate that we have the models and computational wherewithal to properly evaluate acute and chronic intakes of Th-232 and Th-228 based on Ac-228 and Pb-212 chest burden measurements. In addition, the default thorium referred to as "triple separated thorium" that will be used in dose reconstructions at Fernald is introduced in this paper.
>
> *Evaluation of Fernald Ac-228/Pb-212 Chest Count Data*, April 18, 2013. In this paper we review Ac-228/Pb-212 chest counts from Fernald, adjust these results for bias, and develop decision levels for each radionuclide.
>
> *Activity Ratios for Various Types of Thorium*, June 21, 2013. In this paper we explore the levels of Ac-228 and Pb-212 expected to be present in the chest after intakes of various mixtures of Th-232/Th-228.
>
> *Approximate Evaluation of Pb-212 Chest Counts Following Intakes of Thorium,* July 19, 2013. In this paper we present methods for using IMBA to make conservative estimates of Th-232 intakes from Pb-212 chest burden measurements, which facilitates dose reconstructions when an overestimate of dose is appropriate.

Taken together, the information in these four papers provides the technical basis and implementing procedures needed to perform a dose reconstruction for an individual with Ac-228 and Pb-212 chest count results.

The decay scheme of Th-232 down to Pb-212 is shown in Figure 1. The radionuclides of interest, i.e., those that can be quantified with a chest count, are the Ac-228 and the Pb-212. We chose to evaluate thorium intakes using primarily the Pb-212 chest count data rather than the Ac-228 chest count data. This paper summarizes the reasons for this decision, using 1980 chest counts from Fernald to illustrate.

Figure 1. Decay scheme of Th-232.

$$^{232}Th \xrightarrow{1.405\times10^{10}\,y} {}^{228}Ra \xrightarrow{5.75\,y} {}^{228}Ac \xrightarrow{6.13\,h} {}^{228}Th$$

$$^{228}Th \xrightarrow{1.91\,y} {}^{224}Ra \xrightarrow{3.62\,d} {}^{220}Rn \xrightarrow{55.6\,s} {}^{216}Po \xrightarrow{0.146\,s} {}^{212}Pb \xrightarrow{10.6\,h}$$

Ac-228 and Pb-212 Kinetics

A chemical separation or stripping of the thorium will remove all non-thorium elements, leaving (more or less) only the Th-232 and Th-228. Immediately after separation, the daughters of Th-232 and Th-228 will start to grow in. This process of ingrowth impacts the use of Ac-228 and Pb-212 for estimating the intake of the parent Th-232 in different ways. Specifically:

Ac-228

A couple of days after separation, the Ac-228 present is equal to the amount of Ra-228 that is present. The amount of Ac-228 present is not necessarily related to the amount of Th-232 present because the Ra-228 has a half-life long enough to permit its presence in the workplace for years independent of its parent Th-232. Starting with pure Th-232, the amount of Ac-228 present is very sensitive to the length of time that has elapsed since the separation of the Th-232 from its progeny.

Pb-212

A few weeks after separation, the Pb-212 present is equal to the amount of Th-228 that is present, less any Rn-220 that is lost from the body. The loss of Rn-220 from the body is expected to be minimal because of its short half-life, and the ICRP biokinetic model for inhaled Th-232 explicitly accounts for this loss. Thus, if Pb-212 is observed then there must necessarily be Th-228 present, and if there is Th-228 present then there must be Th-232 present. However, the ratio of Th-232 to Th-228 is sensitive to the number and timing of chemical separations that have been performed on the thorium.

To illustrate the practical consequences of these characteristics of Ac-228 and Pb-212, both will be used to evaluate a chest count performed at Fernald in 1980.

Fernald Chest Counts

The Ac-228 and Pb-212 results for all 184 chest counts performed in 1980 at Fernald are plotted in Figure 2. We are interested in the counts where both Ac-228 and Pb-212 are above the decision level of 0.12 nCi, which are shown in Figure 3. The blue lines in these plots have a slope of 1 and intercept of 0, indicating the case where the Ac-228 activity equals the Pb-212 activity. The difference between the Ac-228 activity and the blue line is of no practical significance, as is shown in Figure 4 where ± 30% error bars, representing typical measurement uncertainty, are added to the plot.

Figure 2. All Ac-228 and Pb-212 results for 1980 (in nCi) for 184 chest counts performed in 1980. The solid blue line indicates where the Ac-228 equals Pb-212.

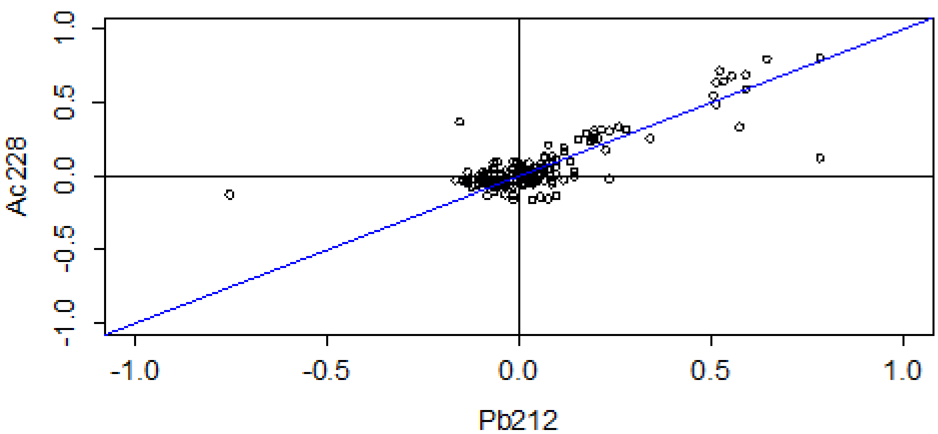


Figure 3. All Ac-228 and Pb-212 results (in nCi) for 27 chest counts performed in 1980 where both counts were above the decision level of 0.12 nCi. The count indicated

by the solid red point has 0.64 nCi of Ac-228 and 0.51 nCi of Pb-212. The solid blue line indicates where the Ac-228 equals Pb-212.

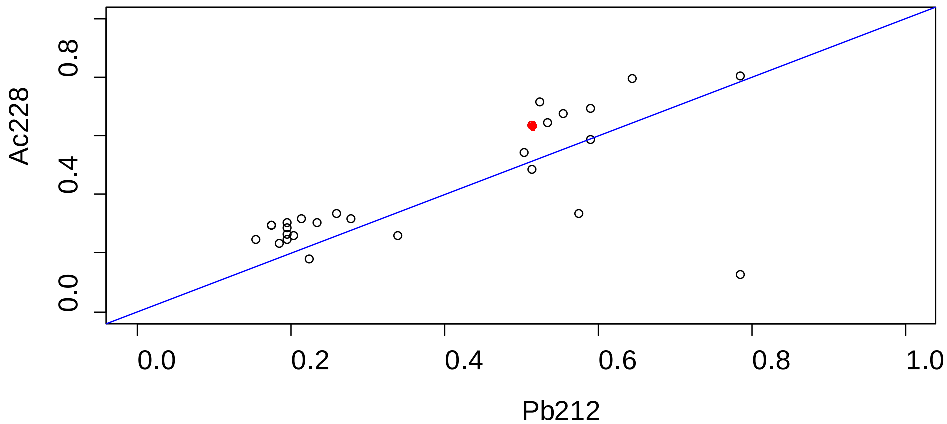
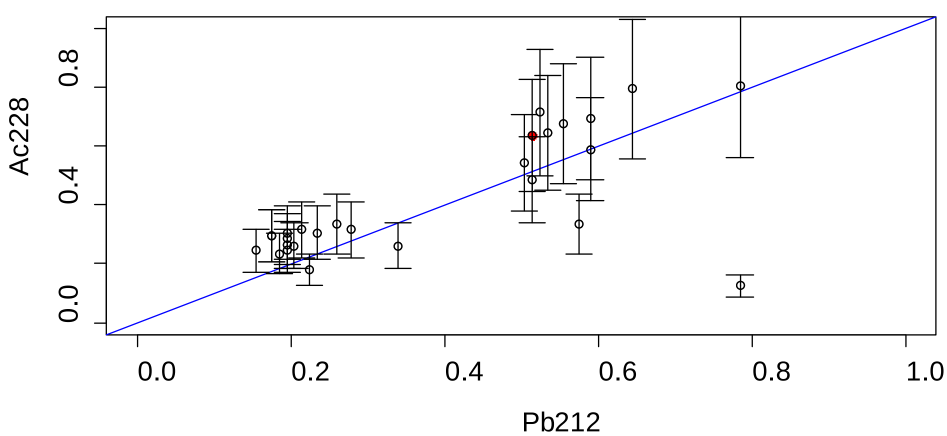


Figure 4. Same plot as shown in Figure 2 with the addition of ±30% error bars representing measurement uncertainty.



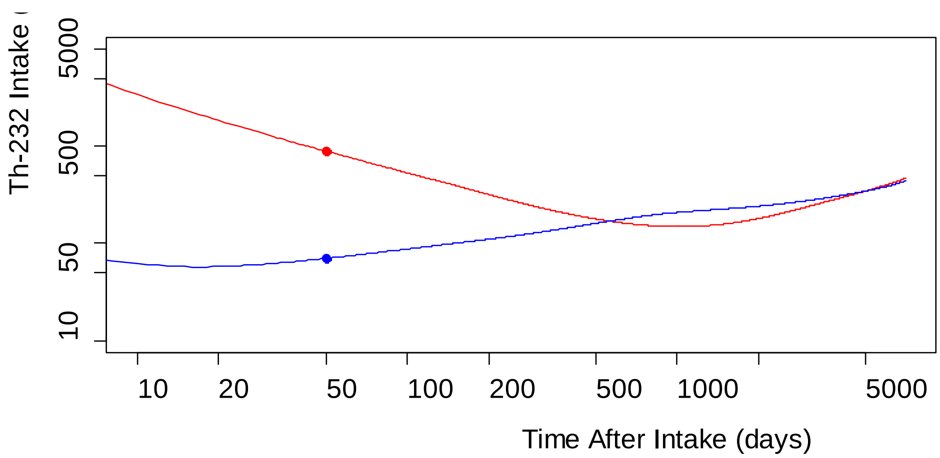
Intake Calculations

The count indicated by the solid red point in Figure 3 has an Ac-228 activity of 0.64 nCi and a Pb-212 activity of 0.51 nCi. Acute inhalation intakes of Type S Th-232 can be calculated from the Ac-228 chest count by assuming that the measurement was performed at a particular time after intake of "pure" thorium (no Ra-228). For example, if a 0.64 nCi chest burden of Ac-228 was measured at 50 days post intake, the estimated intake of Th-232 is 892 nCi. Note that this intake estimate is independent of the Th-232 to Th-228 ratio (i.e., it is independent of the number of separations performed on the thorium).

Acute inhalation intakes of Type S Th-232 can also be calculated from the Pb-212 chest count by assuming that the measurement was performed at a particular time after intake of pure thorium that has a specified Th-232 to Th-228 ratio. For example, if a 0.51 nCi chest burden of Pb-212 was measured at 50 days post intake, the estimated intake of Th-232 is 70 nCi, assuming that we are dealing with triple-separated thorium (which specifies a Th-232 to Th-228 ratio).

Repeating these calculations for chest counts performed at days 1 through 7000 following the acute intake creates the intake lines shown in Figure 5 (which one should note has log-log scales).

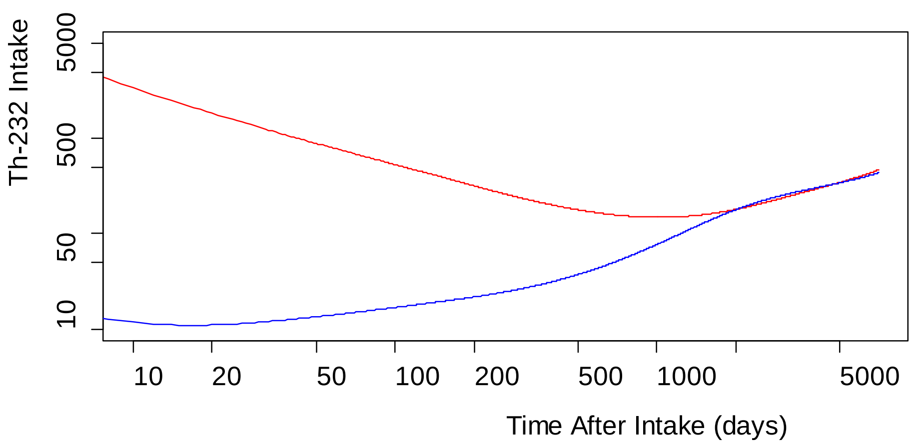
Figure 5. Intakes of triple-separated Type S Th-232 calculated from chest burdens of 0.64 nCi of Ac-228 (red line) and 0.51 nCi of Pb-212 (blue line) as a function of time after an acute inhalation intake the chest burden was measured.



After a year or two the Th-232 intakes estimated from the Ac-228 and Pb-212 are similar enough to be considered equal for all practical purposes. Prior to this time the Th-232 intakes estimated from the Ac-228 are significantly higher than the Th-232 intakes estimated from the Pb-212, reflecting the strong dependence of the Ac-228 burden on the time elapsed since separation.

Assuming something other than triple-separated thorium will increase the difference, as shown in Figure 6 where the ratio of Th-232 to Th-228 is assumed to be 1:1 (i.e., an equilibrium thorium mixture).

Figure 6. Intakes of equilibrium Type S Th-232 calculated from chest burdens of 0.64 nCi of Ac-228 (red line) and 0.51 nCi of Pb-212 (blue line) as a function of time after an acute inhalation intake the chest burden was measured

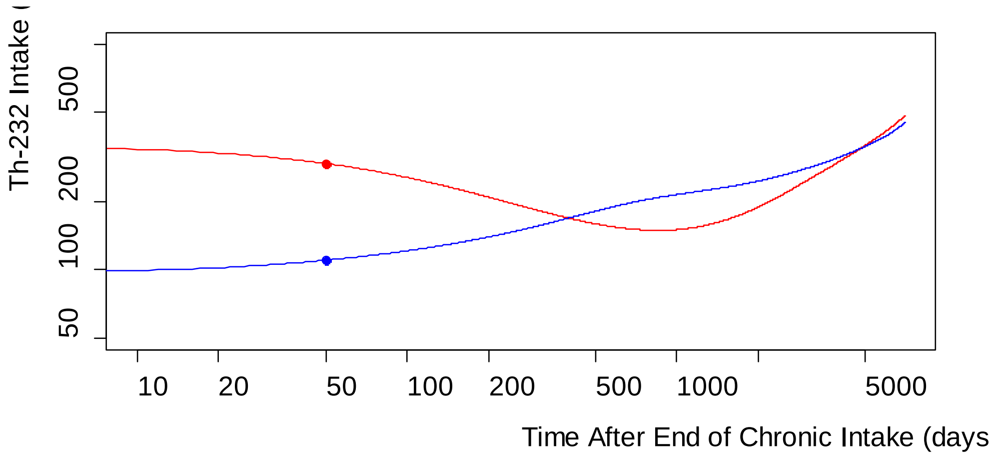


Thus, given that we are dealing with an acute inhalation intake of triple-separated Type S thorium, the chest count indicating an Ac-228 activity of 0.64 nCi and a Pb-212 activity of 0.51 nCi had to have been performed at some time much greater than 50 days post intake. Indeed, because thorium separation activities ceased at Fernald in 1979, a time post separation of over a year is most likely in this case.

In general, if a Th-232 intake calculated from a measured Ac-228 chest burden is much larger than the Th-232 intake calculated from a measured Pb-212 chest burden, we have either assumed the wrong time post separation for the chest count or there is unsupported Ra-228 present in the inhaled material (see *Evaluation of Fernald Ac-228/Pb-212 Chest Count Data*). In either case, the Th-232 intake calculated from the Pb-212 is considered to be the more accurate intake estimate.

In the case of a chronic intake, there is less of a difference between intakes estimated from the Ac-228 and Pb-212 chest burdens. For example, if a 0.64 nCi chest burden of Ac-228 was measured at 50 days after the end of a 365-day chronic intake of triple-separated Type S thorium, the estimated intake of Th-232 is 297 nCi. If a 0.51 nCi chest burden of Pb-212 was measured at 50 days after the end of the chronic intake, the estimated intake of Th-232 is 110 nCi. Repeating these calculations for chest counts performed at days 1 through 7000 after the end of a 365-day chronic intake creates the intake lines shown in Figure 7.

Figure 7. Intake of triple-separated Type S Th-232 calculated from chest burdens of 0.64 nCi of Ac-228 (red line) and 0.51 nCi of Pb-212 (blue line) as a function of time after the end of a 365-day chronic inhalation intake. For example, day 20 on the x-axis is 20 days after the end of the 365-day chronic intake.



Conclusion

Thorium-232 intakes can be estimated from measurements of Ac-228 or Pb-212 in the chest. Here and in previous white papers we have presented technical discussions that support our use of Pb-212 chest burdens combined with the assumption of triple-separated thorium to estimate Th-232 intakes. This approach is unlikely to underestimate the Th-232 intake and avoids the potential gross overestimates associated with the use of Ac-228.

ATTACHMENT C

In Development

ATTACHMENT D

Thorium (Class W) inhalation intake rate at Fernald based on 10% of Th-232 DAC

100% Th-232 DAC	5.00E-13 µCi/cm^3	
10% Th-232 DAC	5.00E-14 µCi/cm^3	(5.00E-14 µCi/cm^3 x 2.22 E+06 dpm/µCi) = 1.11E-07 dpm/cm^3
		(1.11 E-07 dpm/cm^3 based on 2.22E+06 dpm/µCi)
Work Year	2000 hr/yr	(2000 hr/yr / 8 hrs/d) = 250 days
Breathing Rate (ICRP 68)	1.2 m^3/hr	(1.2E+06 cm^3/hr based on 1.00 E+06 cm^{3}m^3)
OCAS TIB-009	0.2	(Intake per workday, not calendar day = 250 days)
Annual Inhalation Intake of Th-232	266.400 dpm/yr	(1.11E-07 dpm/cm^3 x 1.2 E+06 cm^3/hr x 2000 hr/yr = 266.4 dpm/yr)
Annual Ingestion Intake of Th-232	5.550 dpm/yr	(1.11E-07 dpm/cm^3 x 1.00 E+06 cm^3/m^3 x 0.2 x 250 d/yr = 5.55 dpm/yr)

Note: Both 10 CFR 835 and DOE 5480.11 DAC for Th-232 (Class W) is 5.00 E-13 µCi/cm^3

ATTACHMENT E

Interim Technical Basis for Assigning Doses from Effective DAC (EDAC) BZ Results

Historically the Fernald site used the most restrictive DAC to limit exposures to airborne thorium and its daughter products. The standard procedure was to count the air samples in a low-background proportional counter. This instrument was capable of measuring total alpha activity (beta-gamma activity was ignored by the appropriate setting on a pulse-height discriminator). By 1995, it was recognized that this method, while conservative, did not provide accurate results (SRDB 3547). The solution was to develop an effective DAC (EDAC) for each specific mixture of radionuclides that would apply to specific locations and/or operations on site. The equation used was:

$$EDAC = \frac{1}{\sum \frac{f_i}{DAC_i}} \ (Equation\ 1)$$

Where:
f_i = the activity fraction of isotope *i* in the airborne mixture
DAC_i = The DAC of isotope *i*" (SRDB 3560)

If the mixture in question included beta emitters, then it was necessary to adjust the EDAC calculated from the above equation so that the exposure in EDAC-hours was calculated correctly. This was done by multiplying the EDAC by the fraction of the isotopes that were alpha emitters. The value of the alpha-count-adjusted EDAC is not important for dose reconstruction.

The HIS-20 database was implemented at Fernald in the mid-1990s. Some of the data it contains were migrated from legacy health and safety databases. The HIS-20 database is the source of the DOE-provided breathing zone (BZ) data. DOE has also provided data extracted from HIS-20 to NIOSH in the form of Microsoft Access tables. The data in the BZ table indicate thorium BZ results first appear in 1993. The first EDAC, designated BL-65 (Building 65), was recorded in 1996. A technical basis for this EDAC had been published in 1995 (SRDB 3547). The four other EDACs in HIS-20 are not formally documented in any of the documents captured so far. This paper provides an interim method of calculating intakes from the EDAC data for dose reconstruction purposes.

The Table E-1 summarizes the EDAC results in the Fernald HIS-20 database which was provided to NIOSH.

Table E-1, Count of Effective DAC Results in HIS-20

NUCLIDE	Count of Results	Min Year	Max Year
BL-13	924	2003	2004
BL-65	5260	1996	2003
CELL 8	2	2005	2005
KS-65	23034	2004	2006
RT-210	489	2001	2006

The likely definitions for BL-13, BL-65, and KS-65 have been located. These and potential definitions for CELL-8 and RT-210 are discussed in the following sections.

BL-13

The BL-13 EDAC is documented in a memorandum from Connell to Kent and Thiel, October 13, 2003 (SRDB 129871) and SD-1064, "Technical Basis: Air Sampling Plan for Demolition Closure Projects," Rev 6, February 9, 2004 (SRDB 132933). The EDAC calculated for a mixture of Th-232, Th-230, Th-228, and total uranium was 3.28E-12 µCi/ml. The author recommended that it be rounded down to 3.0E-12 µCi/ml to be consistent with another project. The mean activity fractions from SD-1064 appear in Table E-2. It should be noted that the name given to this EDAC in SD-1064 was "B13A." However, there are no results in HIS-20 with this designation, and it was assumed that the results were entered into HIS-20 as "BL-13."

Table E-2, Activity Fractions for the BL-13 EDAC

Isotope/Element	Activity Fraction
Th-232	0.083
Th-230	0.259
Th-228	0.098
U-total	0.560

Dose Reconstructors should multiply the reported number of BL-13 DAC-hours by 3.0E-12 µCi/ml/DAC and the breathing rate (1.2E+06 ml/hour) to get the total intake. They then should multiply the total intake by the respective activity fractions for Th-232, Th-230, Th-228, and total uranium, as follows:

- Th-232: intake (µCi) = reported DAC-hrs × 3.0E-12 µCi/ml/DAC × 1.2E+06 ml/hr × 0.083
- Th-230: intake (µCi) = reported DAC-hrs × 3.0E-12 µCi/ml/DAC × 1.2E+06 ml/hr × 0.259
- Th-228: intake (µCi) = reported DAC-hrs × 3.0E-12 µCi/ml/DAC × 1.2E+06 ml/hr × 0.098
- U-total: intake (µCi) = reported DAC-hrs × 3.0E-12 µCi/ml/DAC × 1.2E+06 ml/hr × 0.560

BL-65

The BL-65 EDAC documented in *Technical Basis for the Effective DAC for Th^{232} Stored in Building 65*, Rev 0, October 20, 1995 (SRDB 3547). The technical basis shows that the activity of Th-230 is insignificant (< 3%) compared to the other isotopes in this particular mixture (see Attachment B of SRDB 3547). In addition, its DAC is higher than the effective DAC calculated. Therefore, the Th-230 is ignored. The other long-lived isotopes are assumed to be in equilibrium. Thus, Th-232, Ra-228, Ac-228, Th-228, and Ra-224 are each assumed to represent 20% of the activity. The resulting EDAC based on total activity is 2.22E-12 µCi/ml. Dose Reconstructors should multiply the reported number of BL-65 DAC-hours by 2.22E-12 µCi/ml/DAC and the breathing rate in ml/hour to get the total intake. They then should multiply the total intake by 0.2 to get the intakes of Th-232, Ra-228, Ac-228, Th-228, and Ra-224, as follows:

- Th-232: intake (µCi) = reported DAC-hrs × 2.22E-12 µCi/ml/DAC × 1.2E+06 ml/hr × 0.20
- Ra-228: intake (µCi) = reported DAC-hrs × 2.22E-12 µCi/ml/DAC × 1.2E+06 ml/hr × 0.20
- Ac-228: intake (µCi) = reported DAC-hrs × 2.22E-12 µCi/ml/DAC × 1.2E+06 ml/hr × 0.20
- Th-228: intake (µCi) = reported DAC-hrs × 2.22E-12 µCi/ml/DAC × 1.2E+06 ml/hr × 0.20
- Ra-224: intake (µCi) = reported DAC-hrs × 2.22E-12 µCi/ml/DAC × 1.2E+06 ml/hr × 0.20

<u>KS-65</u>

The K-65 silos contained high concentrations of radium-bearing wastes from former production activities. The activity fractions for the two K-65 silos are documented in Table 5-16 of ORAUT-TKBS-0017 Rev 00 (ORAUT 2004) and appear in Tables E-3 and E-4, below.

Table E-3, Isotopic Composition of K-65 Silo 1

Isotope	Activity	Activity Fraction
U-total	1.68 nCi/g	1.61E-03
Ac-227	7.67 nCi/g	7.36E-03
Pb-210	202 nCi/g	1.94E-01
Po-210	281 nCi/g	2.70E-01
Ra-226	477 nCi/g	4.58E-01
Th-228	2.28 nCi/g	2.19E-03
Th-230	68.9 nCi/g	6.62E-02
Th-232	1.11 nCi/g	1.07E-03

Table EA-4, Isotopic Composition of K-65 Silo 2

Isotope	Activity	Activity Fraction
U-total	2.37 nCi/g	3.04E-03
Ac-227	6.64 nCi/g	8.50E-03
Pa-231	4.04 nCi/g	5.17E-03

Pb-210	190 nCi/g	2.43E-01
Po-210	231 nCi/g	2.96E-01
Ra-226	263 nCi/g	3.36E-01
Th-228	7.36 nCi/g	9.42E-03
Th-230	76.2 nCi/g	9.75E-02
Th-232	0.99 nCi/g	1.26E-03

The EDAC that was designated "KS-65" was not located in the documentation. Calculations were made for each of the silos using the Equation 1, above.

The resulting EDACs for total activity were 3.2E-11 µCi/ml and 2.0E-11 µCi/ml for Silos 1 and 2, respectively. Using the higher of the two would produce the most favorable intakes. Therefore, Dose Reconstructors should multiply the reported number of KS-65 DAC-hours by 3.2E-11 µCi/ml/DAC and the breathing rate in ml/hour to get the total intake. They then should multiply the total intake by the respective activity fractions in the above tables. Two calculations will be necessary since not only are the activity fractions different, but also Table E-4 contains Pa-231 in addition to the isotopes in Table E-3.

The calculations are as follows:

Silo 1

- U-total:intake(µCi) = reported DAC-hrs × 3.2E-11 µCi/ml/DAC × 1.2E+06 ml/hr × 1.61E-03
- Ac-227: intake (µCi) = reported DAC-hrs × 3.2E-11 µCi/ml/DAC × 1.2E+06 ml/hr × 7.36E-03
- Pb-210: intake (µCi) = reported DAC-hrs × 3.2E-11 µCi/ml/DAC × 1.2E+06 ml/hr × 1.94E-01
- Po-210: intake (µCi) = reported DAC-hrs × 3.2E-11 µCi/ml/DAC × 1.2E+06 ml/hr × 2.70E-01
- Ra-226: intake (µCi) = reported DAC-hrs × 3.2E-11 µCi/ml/DAC × 1.2E+06 ml/hr × 4.58E-01
- Th-228: intake (µCi) = reported DAC-hrs × 3.2E-11 µCi/ml/DAC × 1.2E+06 ml/hr × 2.19E-03
- Th-230: intake (µCi) = reported DAC-hrs × 3.2E-11 µCi/ml/DAC × 1.2E+06 ml/hr × 6.62E-02
- Th-232: intake (µCi) = reported DAC-hrs × 3.2E-11 µCi/ml/DAC × 1.2E+06 ml/hr × 1.07E-03

Silo 2

- U-total: intake (µCi) = reported DAC-hrs × 3.2E-11 µCi/ml/DAC × 1.2E+06 ml/hr × 3.04E-03
- Ac-227: intake (µCi) = reported DAC-hrs × 3.2E-11 µCi/ml/DAC × 1.2E+06 ml/hr × 8.50E-03
- Pa-231: intake (µCi) = reported DAC-hrs × 3.2E-11 µCi/ml/DAC × 1.2E+06 ml/hr × 5.17E-03
- Pb-210: intake (µCi) = reported DAC-hrs × 3.2E-11 µCi/ml/DAC × 1.2E+06 ml/hr × 2.43E-01
- Po-210: intake (µCi) = reported DAC-hrs × 3.2E-11 µCi/ml/DAC × 1.2E+06 ml/hr × 2.96E-01
- Ra-226: intake (µCi) = reported DAC-hrs × 3.2E-11 µCi/ml/DAC × 1.2E+06 ml/hr × 3.36E-01
- Th-228: intake (µCi) = reported DAC-hrs × 3.2E-11 µCi/ml/DAC × 1.2E+06 ml/hr × 9.42E-03
- Th-230: intake (µCi) = reported DAC-hrs × 3.2E-11 µCi/ml/DAC × 1.2E+06 ml/hr × 9.75E-02
- Th-232: intake (µCi) = reported DAC-hrs × 3.2E-11 µCi/ml/DAC × 1.2E+06 ml/hr × 1.26E-03

CELL-8

The Onsite Disposal Facility (OSDF) was used to dispose of wastes, such as contaminated soil and building rubble that were too low-level to justify sending off site. The OSDF was filled in sections, called cells. The waste would have been characterized prior to being placed in the cells. Cell 8 was the last cell filled. The final cap of cell 8 was installed in 2006. There are only 2 results in HIS-20 with this EDAC designation, comprising less than 0.01% of the results. The results are for 2 individuals on 9/6/2005. Both wore respirators and both results were below the minimum detectable DAC-hours shown in the HIS-20 records. Neither individual is a claimant. It is suggested that the method for addressing this EDAC be deferred since it may never be needed.

RT-210

The remaining EDAC, RT-210, comprises only 1.7% of the results. There were two Radon Treatment (RT) Systems. Because of the relatively small number of results, it is assumed that the RT-210 results apply to workers at the treatment systems. The first system was a temporary arrangement constructed around 2001 that was used to lower radon emissions from the K-65 silos while the material was in storage. Little information has been found for this system. Construction of the new Radon Control System (RCS) for Silos 1 and 2 (as well as some other facilities) was completed and operations began in 2003. The RCS was designed to draw radon gas from the headspace inside Silos 1 and 2 and reduce the concentration of gas by at least 95 percent to protect workers during removal of the K-65 material. The Silo 1 and 2 wastes were removed by slurry, solidified, and placed in casks. The casks were shipped to an off-site facility for disposal.

The date range for RT-210 is 2001-2006, which covers both radon treatment systems. In 2006, the Silos 1 and 2 Remediation Facility, Transfer Tank Area (TTA), and Radon Control System demolitions were completed.

The following description of the Fernald RCS was located in a Corps of Engineers document:

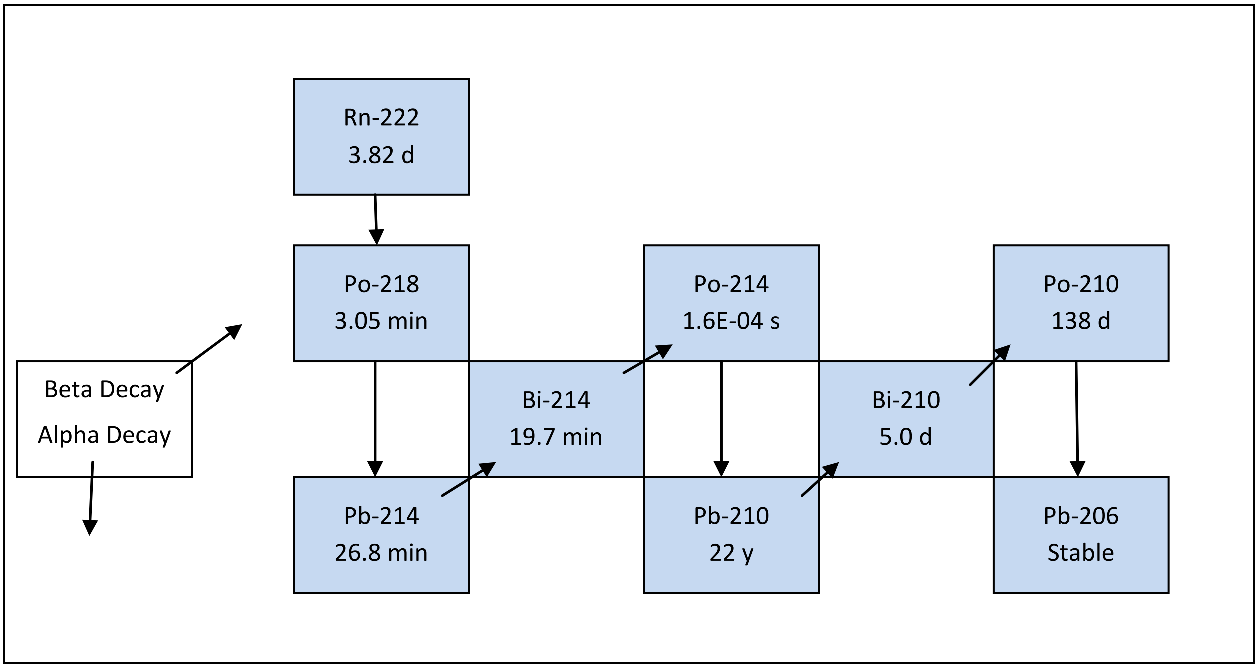
> Centrifugal fans pulled radon-laden gas from the sources through the roughing filters for initial particulate daughter removal. The air stream was chilled and dried to enhance the dynamic adsorption capacity of the activated carbon. Condensed liquids from the gas stream were transferred to shielded holdup tanks until transfer and disposition in the Remediation Facility could be completed. There were four carbon beds, each containing 20,400 kg (45,000 lbs) of carbon. These beds were configured so that any two of the four beds were in use at any given time. This allowed for decay time of the alternate two beds, whereby no carbon changes were required over the life of the project. The RCS reduced radon concentration to less than 2% of the inlet concentration and the carbon bed outlet air was either recycled to the silos or exhausted through the 46-m (150-ft) tall stack. Approximately four inches of carbon steel shielding was designed and installed adjacent to the carbon beds to reduce general area dose rates … ventilation requirements were considered for all tasks where radon concentrations greater than 0.01 WL are expected in the air in occupied spaces, such as the TTA and RCS buildings. (http://www.lrb.usace.army.mil/Portals/45/docs/FUSRAP/NFSS/EI/nfss-feasstudy-techmemo-wdoandfll-2011-07.pdf)

The Ra-222 decay chain is shown in Figure E-1. During the operation of the facility, the three long-lived daughters, Pb-210, Bi-210, and Po-210, built up in the system's piping and filters. These isotopes would have been the concern for worker exposures during shutdowns and maintenance (e.g. filter changes). Information from the site indicates that the RT-210 EDAC was most likely calculated assuming equilibrium among the three isotopes (SRDB 130226). The activity fractions are shown in Table E-5.

Table E-5, Activity Fractions for the RT-210 EDAC

Isotope/Element	Activity Fraction
Pb-210	0.333
Bi-210	0.333
Po-210	0.333

Figure E-1, Radon-222 Decay Chain Showing Half Lives



The following DACs were obtained from 10CFR835, Appendix A:

Pb-210: 1E-10 µCi/ml
Bi-210: 1E-07 µCi/ml
Po-210: 3E-10 µCi/ml

From the DAC values and an activity fraction of 0.333 for each isotope an EDAC of 2.25E-10 µCi/ml was calculated. Dose Reconstructors should multiply the reported number of RT-210 DAC-hours by 2.25E-10 µCi/ml/DAC and the breathing rate in ml/hour to get the total intake. They then should multiply the total intake by 0.333 to get the intakes of Pb-210, Bi-210, and Po-210, as follows:

- Pb-210: intake (µCi) = reported DAC-hrs × 2.25E-10 µCi/ml/DAC × 1.2E+06 ml/hr × 0.333
- Bi-210: intake (µCi) = reported DAC-hrs × 2.25E-10 µCi/ml/DAC × 1.2E+06 ml/hr × 0.333
- Po-210: intake (µCi) = reported DAC-hrs × 2.25E-10 µCi/ml/DAC × 1.2E+06 ml/hr × 0.333

ATTACHMENT F

Analyses of POTENTIAL Thoron Exposure AT FMPC

Bryce L. Rich

Introduction:

From the beginning of FMPC operations in late 1953 until the "completion of the disposition of the containerized waste inventory" (ref. 33) there have been uranium and thorium processes (Summarized in Table 1 from References 11 through 17) with feed materials and the associated waste materials that have resulted in elevated levels of 3.823 day half-life Rn-222 (Radon) and 56 second half-life Rn-220 (Thoron) plus their particulate daughter products. Radon is the first daughter product of Ra-226, which was present in significant quantities in the raffinates from processing high uranium-bearing pitchblende ores. The elevated Radon exposure levels at FMPC from this source are addressed in reference #10, ORAUT-RPRT-0052. The topic of the present paper addresses the potential exposures resulting from elevated levels of Thoron during processing and/or storage of thorium at FMPC.

As illustrated in the decay diagram of Th-232 (Figure F-1), thoron is the second daughter product of Th-228 and in a couple of weeks, following processing for thorium purification, can be considered to be in full equilibrium with the parent Th-228. Th-228 is a third daughter product of the long-lived Th-232 and generally in 40-65% equilibrium for materials processed at FMPC. (Figure F-2) The degree of equilibrium is dependent upon both 1) the decay of Th-228 without replenishment from the 5.7 yr half-life Ra-228 after removal of the thorium daughters and 2) the time it takes the Ra-228 to build into equilibrium with Th-232 (Figure F-2). For purposes of this analysis 65% equilibrium is assumed as the default [1]. Th-228 is also a first daughter product of U-232, which could have been present in small quantities from recycled thorium materials from Hanford in the 1977-1979 process, but not in sufficient levels from this source to result in a significant change in default defined in this paper [2].

Figure F-1. Th-232 decay diagram, including the Rn-220 (Thoron) decay chain

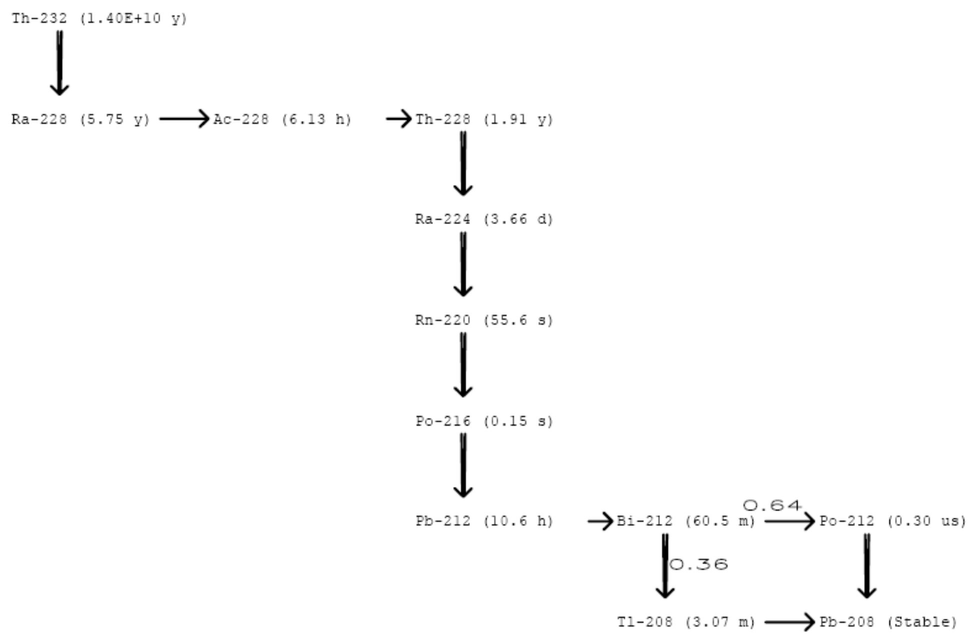
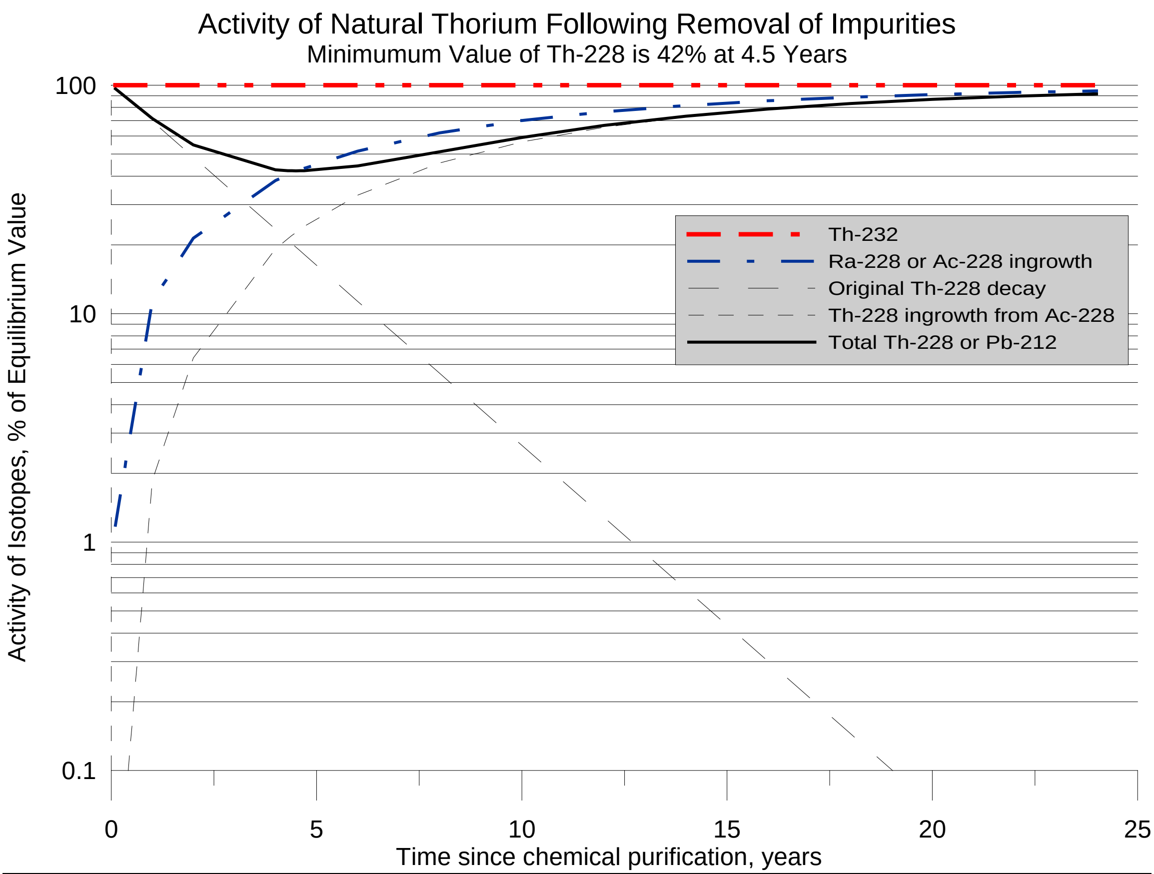


Figure F-2. Decay and Buildup of Th-228 and daughters following processing



Thoron was present and a portion released during the processing and storage of metric tons of a variety of forms of thorium. Though this radioactive gas and its short-lived daughter products are present in variable levels as a natural background, elevated levels with those of radon have been identified and studied and associated with increased respiratory cancer potential, i.e. uranium miner studies and others (ref. #s 1, 2, 3, 4, 6, 7, 9, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31 & 32).

The primary focus of the FEMP radiological safety programs (ref. #18 & 19) for thorium was to define the thorium air concentrations in air in the work place coupled with in vivo lung counts for Thorium, the results of which provided the means of controlling worker exposures to levels below the then-current permissible levels. In addition the metric ton quantities of thorium in process (with the measured particulate releases) or storage provided sources of elevated thoron gas release with its subsequent daughter products. The records (ref 5 & 17) indicate that there was an awareness of the potential for exposure to thoron and its daughter products through documentation of reported “thoron” measurements and holding of the routine breathing zone (BZ) and general area (GA) samples for up to 96 hours to allow the short lived Radon and Thoron daughter products to decay. This provided a more meaningful measure of the long-lived thorium concentrations (ref. #17). Since air activity sample analyses specifically for Thoron daughters are insufficient to directly document the routine concentrations in the work places at all times, an approach for bounding the possible workplace concentrations of Thoron and daughter products is presented. This section presents the methods and considerations of bounding the work place exposures to Thoron and primarily the short-lived daughter products, based upon theoretical analyses and conservative assumptions.

Thorium Process Inventories and Thoron Potential:

During the 35 year operating history of the Fernald site, approximately 70% of those years (24 years) involved the production of 10s to 100s of MTTh parts and products on an annual basis for a total of over 3800 MTTh (Table F-1). The production of that quantity of products required processing of approximately 4200 MTTh, and leaving over 750 MTTh of scrap and waste materials (See Tables F-1 and F-5). On the surface this appears to be a large amount, although the primary material processed at FMPC was uranium. Several historical texts refer to amounts of thorium being “minor” in nature, since the mass of thorium was generally less than 1% of the mass of Recycled Uranium receipts alone. Still the tens to hundreds of metric tons of thorium in most of the FMPC facilities at any given time during the operational history was a recognized hazard and a source of thoron gas (Rn-220), a very short lived (56 sec) daughter product of Th-228. Table F-1 outlines the rough thorium mass balance and estimated inventories during the indicated time periods.

Table F- 1. FMPC Thorium historical mass balance (References 11-17)

Plant Primary Buildings	Time Period	Quantities (MTTh) *			Operations and Materials
		Daily	Annual	Total	
Plant 9	1954-1956	0.5 – 0.6	100-200	380	ThF_4 to metal and machining of cores for reactors. Wastes stored in Plants 1 & 9 storage areas.
Plant 4	1954-1956	0.5 – 0.6	150-300	461	Th oxide conversion to ThF_4 for use in Plant 9
Plant 6	1959-1963	0.02	10-20	80	Converted Furnace for Plant 9 1954-56 Th recovery from scraps and waste.
Plant 1	1954-	<1	unk	unk	Receive, weigh, sample and store source

	1979				and special materials.
Pilot Plant	1954-1956, 1964-1979	0.01 - 0.75	8-381	2558	68% of FMPC Th processed in PP. Metal production, Dense thoria, Th nitrate to thoria gel, Th hydroxide production, processes developed for scale up to production levels.
Plant 8	1965, 1968-1972	0.025	92	303	ThF_4 to Th hydroxide, Th sump cake calcined, Th residue processing to Th hydroxide
Plant 2/3	1968	0.12	45	45	Short term denitration experiment and uranium recovery from thorium hydroxide from plant 8.
Total Processed				3827+ plant 1	
FMPC waste pits	1954-2006 closure	na	na	65	Discarded Th SS material as waste

For perspective - a metric ton of pure thorium metal at the theoretical density occupies a relatively small volume. For example a 10 to 11-gal can (approx. 15" diameter x 15" tall) would weigh approximately 1000 lbs or 0.45 MT. Three of these relatively small cans could hold in excess of a metric ton of thorium.

As shown above, the processing averages during the 24 years of operation were in the 15

– 20 MTTh per month range or <1 MTTh per day, while process feed stocks (preparatory

to processing) quantities in the process facilities could have been in the 2 to 15 MT levels, i.e. during processing campaigns small quantities were probably placed in the process facilities temporarily in queue for the operations [3]. Most of the storage was held in containers in adjacent storage buildings as well as barreled wastes held on pads outside the buildings.

The primary products were metal cores for the RLO and SRP reactors in 1954-56 and a wide range of chemical forms and compounds in the succeeding periods as indicated in Table F-1. Process scraps, out-of-spec product, etc. resulted and became a storage and/or process category. The processes were also varied, ranging from chemical, metallurgical, metal machining, and waste storage, repackaging and shipping.

The primary process in 1977-79 was unusual in that it was primarily a disposal/storage of excess reprocessed thorium materials from Hanford. It involved 6900-gallon tanks of nitrate solution from Hanford, each with 10.8 MTTh for conversion to a stable and hence storable thoria gel. These tanks were received at a rate of up to two per month for a maximum process rate of 21.6 MTTh/mo and again <1 per day and with an overall total of 351 MTTh. U-233 was a contaminant of the thorium at approximately 130 gm/tank load or approximately 12 ppm Th. The total mass of 4.2Kg of U-233 was not separated from the thorium and was stored with the thorium (ref 15).

The total mass inventory is only instructive in relation to the thoron inventory when the equilibrium ratio of Th-228/Th-232 is known in addition to the fact that thorium-bearing materials were seldom 100% thorium. The theoretical activity of Th-232 is 1.09E+5 pCi/g, but for consistency with other reports, including the safety analysis report for the thorium storage facility, a specific activity for Th-232 and it daughters of 0.989E+5 pCi/g of thorium materials will be used as an upper limit, which accounts for lesser densities of thorium compounds and other materials in the product.

The equilibrium age of the thorium processed at FMPC ranged from recently separated to one or two years since separation of the non-thorium daughters [1]. Figure F-2 illustrates the disequilibrium that occurs when thorium is separated from or purified from its daughter elements. Rn-220 is a daughter of the 1.9 yr Th-228, which decreases to approximately 65% of equilibrium with Th-232 in 1 year following separation of the radium and actinium daughter elements and 43% in 5 years post separation. Full Th-232/Th-228 isotopic equilibrium can be assumed for long term storage materials after 35 years or so. 65% will be assumed for the functional period, which represents a material 6 mos. to a year after separation and should be adequately conservative. Assuming 65% equilibrium would make Rn-220 inventory equivalent to 0.64E+5 pCi/g of Th-228 compounds in the processes, and assuming full equilibrium with each of its daughters.

Thorium Waste Repository Locations and Quantities:

FEMP was appointed the DOE thorium materials repository in 1972 and thorium processing was shutdown in 1979. During the storage period up to 1500 MTTh were stored pending final disposal off site in Nevada and Utah. The repository Thorium wastes and surplus thorium materials were accumulated from Fernald and other sites in the repository era from 1972 until the "completion of remediation and the disposition of the containerized waste inventory" or final closure in 2006 (ref. 33). See Table F-2 for a tabulated summary as of 1987of 13,329 drums of thorium plus 184 metric tons of thorium in bulk powders/granules or liquid. Over 689 MTTh were stored in the Pilot Plant warehouse and 747 MT in four other designated storage buildings. The first shipment from this inventory was to the EnviroCare facility in Utah.

Table F-2. Thorium Storage Inventory in 1987 in Metric Tons of Thorium [FMPC History refs. 11-17].

Plant Area	Storage Bldg. #	Drums	Net Weight-lbs	Th Weight-lbs	% Th	MTTh
1	67	5992	426978	333044	78	151
5	65	5599	2492505	711210	29	323
	65W	240	105032	92955	89	42
8	Silo/Bins	Bulk Mtl			50	175
9	64	181	128345	123141	96	56
Pilot Plant	68	1317	971398	745785	77	338
	Liquid Tank	Nitrate Solution			na	351
Total		13329				1436

Factors to Consider in Determining Potential Alpha Energy Concentration (PAEC):

PAEC and PAEE Definitions – The primary dose from Thoron is to the respiratory tract organs and is delivered primarily by the short-lived daughter products (Table F-3). Due to the short radiological half lives and lung clearance of the particulate daughter products there are no practical bioassay measurements to define intake (ref. 8, 9, 20, 24,& 32). Thus the method of choice for dose evaluation is to measure the Potential Alpha Energy Exposure (PAEE), which is the Potential Alpha Energy Concentration in air (PAEC) x the time the worker was exposed. The PAEC is measured in Working Levels (WL) and the PAEE is measured in Working Level Months (WLM). The bounding defaults recommended in this section are listed as WLM, which are directly related to total alpha energy exposure.

Table F-3. Potential Alpha Energy Concentration (PAEC) for Thoron and its Daughters

Isotope	Half-life	Atoms/7.5 pCi	α MeV/atom	PAEC MeV per 7.5 pCi
Rn-220	56 sec	23	14.6	335
Po-216	0.15 sec	<1	Incl	-
Pb-212	10.64 hr	15476	7.8	1.21E+5
Bi-212	60.6 min	1469	7.8	0.12E+5
Po-212	0.3 µsec	-	Incl	-
Tl-208	3 min	73	no **α**	-
Total				1.33E+5

Air Monitoring – From the beginning of operations in the early 1950's the radiological safety program evaluated Rn-222 plus daughter products in work areas with specific Radon and Radon daughter measurements. The health and safety staff was aware of thoron dose potential as evidenced by a number of samples and references to specific Thoron analyses, which have been recovered or mentioned in staff reports (ref. 5, 17). During the period following 1989, when Westinghouse assumed the contractor roll for FEMP, extensive and recorded radon and thoron monitoring was performed across the site (ref. 5). Air monitoring for particulate activity was also performed throughout the production period, and enough air sampling data has been recovered for realistic conclusions/assumptions related to exposure potentials.

Work Place Control Functions (FMPC History refs**.** 11-17**) –** To better understand the workplace ventilation dynamics and air movements, Table F-4 is provided as a summary of the dimensions of the buildings in the FMPC complex which handled thorium in any amount. The process ventilation systems, which include an air moving system for maintaining a negative pressure within the process equipment, a "bag house" particulate filter (a few liquid scrubbers were also used), and individual stacks for release of filtered air to the environs. It was reported that there were a total of 94 of these ventilation systems/stacks during the early time periods, the number of which changed with changing processes and projects. A total of 114 ventilation systems is indicated in Table F-4 and the total stack flow for each building is a summary of all the individual stack flows in that building. Though there were some general building vents for assistance in temperature reduction, these were not used continuously. The air supply for the stack discharge flows came from the building working environs around the containment systems, which in turn enclosed the process equipment. The pressure differential maintained the air flow into the equipment in which the thorium was being processed. As indicated in Table F-4 the air changes per hour for the entire facility volume would average approximately 3 when all the individual ventilation systems were operating. Obviously the air change rate in the immediately vicinity of the individual processes would be higher.

Table F-4. Building dimensions and Ventilation Systems

Building	**Dimensions feet**	**Volume ft^3**	**Volume m^3**	**Number of Ventilation Systems**	**Total Stack ft^3/min**	**Total Facility Chgs/hr**
1	100x160x60	9.6E+5	2.72E+4	15	6.1E+4	3.8
2/3	60x380x67	1.53E+6	4.33E+4	6	3.2E+4	1.3
4	225x165x94	3.49E+6	9.88E+4	12	4.38E+4	0.8
5	650x100x52	3.38E+6	9.57E+4	17	1.5E+5	2.7
+ bldg 55	60x30x51	0.92E+5	2.61E+3	1	4.0E+3	2.6
6	500x200x39	3.9E+6	11.0E+4	6	1.35E+5	2.1
7	110x80x114	1.0E+6	2.83E+4	4	1.7E+4	1.0
8	60x260x48	7.49E+5	2.12E+4	24	8.22E+4	6.6
9	300x225x40	2.7E+6	7.65E+4	4	7.89E+4	1.8
Pilot Plant	210x235x54	2.66E+6	7.53E+4	9	4.37E+5	9.9
64	50x320x22	3.52E+5	1.0E+4	8	1.6E+4	2.7
65	50x210x22	2.31E+5	0.65E+4	8	1.6E+4	4.2
Ave/Total			5E+4 ave	114 total		3.3 ave.

Release Fraction of Stored Materials – Four examples are provided to address the release fraction of both Rn-222 and Rn-220 gasses and provide a basis for estimating the release fraction (RF) of radon gases to the work environs:

1- In order to bound the release of radon gas from a source of stored barrels of known waste concentration, measurements taken in a shipping car (~6E+4 liter volume) with 48 barrels of raffinate wastes with a Ra-226 concentration of 400 nCi/gm were used. This is the maximum measured isotopic characterization of silo waste – determined at a much later date. A level of approximately 25 Ci of Ra-226 was calculated as the inventory in the 48 drum waste shipment. The maximum measured Rn-222 daughter concentration (the highest of a number of samples) in the transport carrier was 400 pCi/l in the unventilated shipping car. Using these values, the de facto Rn-222 release fraction (RF) from the drums is calculated to be 400 pCi/l ÷ (2.5E+13 pCi/6E+4 l) = 1E-6. These shipping containers were "enclosed containers" – but obviously not vapor tight. This is a measurement of Rn-222 with a 3.8 day half-life and the associated higher diffusion capabilities, compared to Rn-220, which would have shown a much lower RF.

2 - Another example and specifically for short-lived thoron gas release is found in the maximum measured Rn-220 daughter levels in Building 65 (0.7E+4 m^3) in 1996. Building 65 is one of the primary DOE repository storage facilities and the maximum of many measurement concentrations was 267 pCi/l. Assuming this measurement was the daughter products of Rn-220, the Rn level would be 1.3E+4 pCi/l . See ref. 2 SRDB 27376 and the discussion of the choice of "Fraction of equilibrium – Feq of 0.02 in the "Equilibrium of Thoron and daughter products Pb-212, Bi-212, Po-212 and Tl-208 discussion.") The facility contained approximately 421 MTTh at the time of the measurement with the associated 27 Ci of Rn-220. Part of the containers had not been double packed and the lower level drums were in poor repair - corroded and leaking. Total release of the Rn-220 inventory would result in 2.7E+13 pCi/0.7E+7 l = 4E+6 pCi/l for an RF of 1.3E+4/4E+6 = 3E-3. There are many unknowns in this example: ventilation of the building, fraction of the stored material containers that were breached, location of the air sample in relation to leaking drums, etc. Hence it will not be used as a quantitative example – other than to indicate that the RF for some storage facility operations will be in the E-3 range and is more likely to be comparable to the storage silo example below.

3 - A third example can be demonstrated through measurements made at the top of the Plant 8, 3000 ft^3 storage silo (an elevated cylinder, 17' dia. x 23' high with conical sections on the bottom and top) with approximately 85 MTTh. Thorium oxide and hydroxide granular material at approximately 50% thorium and a measured density of 200 lbs/ft^3 in the top of the oxides, providing a thorium density of 100 lbs/ft^3. An air activity concentration of 71 WL was measured at the top of the tank, which had a 15 foot high x 17 foot diameter air space in the tank above the thorium materials (1E+05 l). The conical-shaped surface area of the top (center conveyor-deposited) thorium material was calculated as approximately 350 ft^2.

- With a diffusion distance of approximately 2 cm (ref. 1 and assumed 1 inch), the effective thoron quantity available for diffusion to the head space was calculated as:
- 350 ft^2 x 1/12 ft x 100 lbs/ft^3 x 454 gm/lb x 0.64E+05 pCi/gm = 8.5E+10pCi
- This compares to 85 MTTh x 6.4E+10 pCi/MTTh = 5.4E+12 pCi in the total silo or 1.6% of the Rn-220 available for release.

- The maximum Rn-220 in the 1E+05 liter head space volume expected is 8.5E+10 pCi/E+05 l = 9E+5 pCi/l (Total Rn-220 in 1 inch of the surface)
- This is compared to a measured 71 WL= 375 pCi/l Rn-220 /WL [4] 71 WL = 3E+4 pCi/l .
- This results in an effective RF of 3E+4/9E+5 = 3E-02 – of that within 1" of surface.
- Hence the RF considering the total Rn-220 (from 85 MTTh) in the silo is 3E+4/(5.4E+12/1E+5) = 6E-4

From this example we see that the plant 8 storage silo is essentially a big barrel of thorium and the amount of Rn-220 in the head space will be in the order of E-3 to E-4 of the total in the container. Migration of the Rn-220 from the container (big or small) to the work environs will be in the E-6 range (reasonably estimated, based upon Rn-222 migration from barrels of waste).

4 - The fourth example is found in the Plant 8 elevated double bin storage tanks. Similar to the silo example above, a lesser RF is calculated – further verifying the conservatism in the assumptions.

Therefore, it is judged to be conservative to use an RF of 1E-6 for stored inventories in intact but unsealed containers (10 to 50 gal drums, etc.) and 1E-04 for areas immediately in the vicinity of open thorium materials such as silo storage or leaking drums in closed buildings, etc.

Release Fraction of Materials in Process – For process areas the RF can be conservatively calculated based upon general thorium particulate air activity, compared to the total thorium material in process. Routine air sampling in the operating areas recorded thorium concentrations ranging from tens to a few samples in the tens of thousands of d/m/m^3 and mostly in the very early 1954-5 period when processes were being developed. Thus it could be assumed that a 1 MT (1E+6 g) daily process load in a 5E+4 m^3 volume process building in which process releases had resulted in 1E+4 d/m/m^3. However, it is not reasonable to assume that the air concentrations in the building will be at the maximum levels throughout the entire area, and these levels will be assumed to exist in a 20' hemispherical air space near the process equipment (475 m^3). This is based upon the fact that the higher value air samples used were undoubtedly BZ samples taken during high level maintenance, e.g. clean out evolutions, etc. For these reasons it is reasonable to assume that the air samples represented maximum concentrations in the immediate vicinity of the equipment and not of average building concentrations.

1E+6 g (0.64E+5 pCi/g) (2.22 dpm/pCi)/475m^3 = 0.3E+9 d/m/m^3 concentration in the air – if all of the process materials were completely released.

RF = 1E+4/0.3E+9 = 3E-5

Some injection operations (dumping barrels of feed material into hoppers, etc.) could be expected to release the free Thoron in the head space of the container, which would be a ratio of 2 cm to the height of the materials in the container – in the range of 0.1 to 0.01 as indicated in the discussion of release fractions from stored materials. Even then the particulate dusts generated would serve as an absorption/removal mechanism of the daughter products and clear in a short period of time (limiting the exposure time). An RF of 0.01 will be assumed. There was a variety of process equipment that was used, including liquid extraction vessels, furnaces, mixers, etc. all of which were designed for containment.

Equilibrium of Thoron and daughter products Pb-212, Bi-212, Po-212 and Tl-208 – Quoting from Harley, New York University School of medicine, (ref. 2) "The inhaled solid decay products of thoron deposited on the lung airways deliver the bronchial dose." And "---the Feq (fraction of equilibrium) cannot exceed 0.04 and calculations of Feq for indoor radon and thoron confirms the values of 0.4 and 0.02. The value of Feq for thoron is supported by two large data bases, one reported by NIRS with measurements in China and one reported by NYU in residences and also at the former uranium processing facility at Fernald, OH." (ref. #3) Pillai and Paul reported on the Equilibrium of Thoron and its daughters in a monazite processing plant in India values of 0.002-0.007. (ref. #4) 0.02 will be used in this analysis as adequately bounding.

Summary Production Rate and Available Thoron Inventory for Release – As indicated above the average daily production rate was <1 MTTh (ranging from 0.03 – 0.8) with 6E-02 Ci Thoron. Temporary storage within the production facilities during processing campaigns could be 5 – 15 MTTh with the associated 0.3 – 0.9 Ci Thoron. DOE long term storage at FMPC was 100 – 450 MTTh in any of the storage facilities with the associated 6 – 27 Ci Thoron.

Occupancy Time – The nature of storage facilities results in a minimal occupancy time for required functions, i.e. 500 hours per year (or 3 months) is assumed for routine storage conditions, including required repackaging. For long term storage of high integrity storage containers 1 month/year is assumed. The time of occupancy during production periods will be assumed as 1750 hrs per year, since an average 1 MTTh continuous production rate will be assumed. At 1MTTh daily rate the recorded annual quantities processed would be completed in just a fraction of a year.

Demonstrated Local Diffusion Factor – It has been demonstrated that for Thoron daughter concentrations, the concentrations are approximately a factor of 10 higher near the source of the release than the concentration at a distance of 3 ft (ref. #6). Since this is probably ventilation dependent, this demonstrated reduction factor to the breathing zone of workers will be ignored.

Respiratory Protection – It was established practice to wear respiratory protection during processing large volumes/masses of hazardous materials. The wearing of respirators would remove essentially all of the daughter products, through filtration and electrostatic attraction in the filter. However, in the interest of favorability to the claimant due to a few recorded cases of procedure violation (there were sample sheets and other logs that made note of personnel not wearing masks), it will be assumed that no respirators were worn. The notes themselves indicate an unusual condition. Hence this is an admitted overly conservative assumption based upon both 1) the established protection policies and practices and 2) demonstrated difference in calculated intakes of thorium based upon air monitoring results compared to in vivo measured lung burdens.

Summary Assumptions:

- Materials in process – average <1 MT per day and <400 MT per annum.
- Materials in process facilities in temporary storage – 2 to 15 MT, 15 assumed.
- Long term DOE storage – 100 to 450 MT in any given storage location, 450 assumed.
- Specific activity of Thoron in thorium materials at Fernald – 0.64E+5 pCi/g, e.g. Th-228/Th-232 = 0.65
- Facility volume – the facilities were large (averaging 5E+4 m^3). In the interest of conservatism, we assume that the mixing or exposure volume will be near the process equipment and represent approx. 20 foot radius, hemispherical volume in the total facility (475 m^3).
- RF in temporary or long term storage – 1E-6.
- RF in temporary open storage or with compromised containers – 1E-3 to 1E-4.
- RF in general process areas – 1E-5; 1E-4 will be used in plant 9 during process development period in 1954-5.
- Equilibrium factor (Feq) for thoron is 0.02. In a plant configuration with large buildings and engineered ventilation, the recommended 0.02 is judged to be conservative. In this case, it would require a concentration of Rn-220/Po-216 at 375 pCi/l to produce Pb-212/Bi-212 concentrations at 7.5 pCi/l and hence result in 1 WL.
- Diffusion factor of Thoron daughters from source release point – no reduction assumed. Fraction of daughter products near source compared to 3 ft away – 0.1, 1 assumed
- Occupancy time in storage facilities – 500 hours per annum – 1 month for long term storage.
- Occupancy time in process facilities – 1750 hours per annum max.
- Protective respiratory protection – no protective equipment will be assumed.
- Thoron WL = 7.5 pCi/l with 100% equilibrium with daughters = 1.3E+5 MeV/l See Table F-3. WL = 375 pCi/l Rn-220 + Po-216 to produce measured daughter products Pb-212 + Bi-212 at 7.5 pCi/l. (See the discussion of Feq factor 3. and summary item 9 above.)

Table F-5. Summary of Thoron Exposure Estimates

Location & Time	Available Thoron	Reduction &	Eff. Facility	Rn-220/Po-	Pb-212/Bi-	WLM Per

Period	Activity	Calculation Factors	Volume-liters *	216 Activity	212 Activity	year
1954-1955 Plant 9 & Plant 4	1 MTTh /day = 6.4E+10 pCi Rn-220 per day in process	RF 1E-4 Feq 2E-2 Focc.10.2mo per yr	5E+5	12.8pCi/l	0.034 WL	0.35 WLM
	15 MTTh/day = 1E+12 pCi Rn-220 available for release to process facility	RF 1E-6 Feq 2E-2 Focc. 2.9mo per yr	5E+5	2 pCi/l	5.3E-3 WL	0.016WLM
1959-1963 Plant 6	0.02MTTh/day = 1.3E+09 pCi Rn-220/day in process	RF 1E-5 Feq 2E-2 Focc 10.2mo per yr	5E+5	0.026pCi/l	3.5E-3 WL	ns WLM
	2 MTTh/day = 1.3E+11 pCi Rn-220 available for release to process facility	RF 1E-6 Feq 2E-2 Focc. 2.9mo per yr	5E+5	0.26 pCi/l	nsWL	ns WLM
1965 & 1968-1972 Plant 8	0.03 MTTh/day = 2E+09 pCi Rn-220/day in process	RF 1E-5 Feq 2E-2 Focc 10.2mo	5E+5	0.04 pCi/l	ns WL	ns WLM
	2 MTTh/day = 1.3E+11 pCi Rn-220 available for	RF 1E-6 Feq 2E-2 Focc. 2.9mo	5E+5	0.26pCi/l	ns WL	ns WLM

	release to process facility	per yr				
1954-1956 &1964-1979 Pilot Plant	0.8 MTTh/day =5E+10pCi/day in process	RF 1E-5 Feq 2E-2 Focc 10.2mo	5E+5	1 pCi/l	0.0027 WL	0.027 WLM
	15 MTTh/day = 1E+12 pCi Rn-220 available for release to process facility	RF 1E-6 Feq 2E-2 Focc. 3 mo per yr	5E+5	2 pCi/l	0.0053WL	0.016 WLM
1954-1989 Various Storage Sites	300 MTTh = 2E+13 pCi Rn-220 source term in Storage Facilities	RF 1E-4 Feq 2E-2 Focc. 3 mo per yr	1E+7	200pCi/l	0.53WL	1.55WLM
1972-2006 Final Closure Storage	300MTTh 2E+13 pCi Storage Facilities	RF 1E-4 Feq 2E-2 Focc. 1 mo/yr	1E+7	200 pCi/l	0.53WL	0.53WLM

* For maximization purposes the mixing of the thoron and daughters during the processing of thorium is assumed to be in a 20' hemispherical volume immediately around the release point, which in turn is assumed to be the process work station and for the short term stored thorium in the process facilities. For long term storage facilities the volume of the storage facilities was used.

Estimates of possible exposures to Thoron indicate that for some periods and in some locations (primarily long term storage areas in which some extended work periods were required) exposures could be as high as 1.6WLM per year. The work could involve activity with poorly ventilated facilities with open containers, such as repackaging failed containers, preparing for shipment, etc. Even though release factors (RF) are relatively small for both storage configurations and operational conditions and the short half-life of Rn-220 limits the diffusion range in all materials to 2 cm or less possible quantities and exposures can still be of concern. Reference 9 indicates that due to the relatively longer half lives of the daughter products of

Thoron as compared to Radon, significant dose can be experienced with relatively small WLM exposures.

Table F-6 provides a summary of the WLM intake of Rn-220 daughters that could have occurred during processing of thorium. The 1.6 WLM estimate for work in the storage facilities in preparing thorium materials with higher integrity containers and preparations for shipment is conservative. The amount of materials being handled at a given time is not 300 MTTh – and would more likely be at least two orders of magnitude less. It is also an overestimate to assume that the work would require the indicated work load for the 17 year storage period. In addition the work was recognized as requiring special controls, including protective clothing and ventilation. It would be appropriate to account for the fact that work with the materials in storage were "special project" episodes in nature and would not require more than a fraction of full time.

Table F-6. Thoron Exposure Recommendations

Time Period*	Plant	WLM intake each year during period
1954-1956	Plant 9 & 4	0.4
1959-1963	Plant 6	No sig. dose
1965 & 1968-1972	Plant 8	No sig. dose
1977-1979	Pilot Plant	0.03
1972 - 1989	Storage facilities, repackaging, etc.	1.6
1972-2006	Closure Various Storage	0.5

*The time periods listed are primarily recorded operational periods. Time periods not specifically included in the 1950s and 1960s could logically be assigned 0.5 WLM as a conservative accounting for materials in storage.

Since specific work location of individual workers cannot be determined from the records, it would be appropriate to a) make a determination of a claimant as "possibly worked in process areas" or b) "not assigned in process areas." Doses could then be assigned conservatively to workers in the "process area" in the 1954-1971 period of 0.4 WLM/yr, in the 1972-1989 period of 1.6 WLM/yr, and in the 1990-2006 period of 0.5 WLM/yr. Workers not assigned to process areas would have no significant potential for Thoron related exposure.

Attributions and Annotations:

[1] Rich. Bryce L. ORAU Team. Senior Health Physicist. Thorium feed materials were received from a variety of separations facilities stockpiles. A 1 yr delay since separation was judged to be a reasonable average. For purposes of thoron intake estimates, an assumption of as many as 3 separations of the thoron feed-materials will produce a claimant favorable result, while a 65% equilibrium value will provide the claimant favorable estimate of Thoron levels.

[2] Rich, Bryce L . ORAU Team. Senior Health Physicist. The U-233 and trace quantities of U-232 came from Thorium from Hanford in the 1977-79 period. The thorium was "recycled thorium" with a contamination level of approximately 130 gram U-233 per 10.8 MTTh. The total U-233 plant inventory spread through the 351 MTTh was approximately 4.2 kg. Trace levels of U-232 could have been present.

[3] Rich, Bryce L. ORAU Team. Senior Health Physicist. The quantities stored in the process buildings of 15 MTTh awaiting immediate processing is not known from records or interviews. It is reasonable (based upon a knowledge of processing practices) to move materials to a ready point and the amount assumed is considered adequately conservative. The primary storage locations were outside on pads or in adjoining storage facilities.

[4] Rich, Bryce L. ORAU Team, Senior Health Physicist. The Working Level is defined in terms of the Potential Alpha Energy Concentration (PAEC), resulting from 7.5 pCi. In the case of Thoron there is a Feq of 0.02 with the daughter products (See ref. 2), which makes the Rn-220 pCi of 375.

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ATTACHMENT G

Fernald Example Dose Reconstructions for Advisory Board - 2014

Employee 1

Cancer Description: Lung (ICD-9: 162); diagnosed 12/31/2013

Bone (ICD-9: 170.2); diagnosed 12/31/2013

Prostate diagnosed (ICD9 185); diagnosed 12/31/2013

BCC, face (ICD-9: 173); diagnosed 12/31/2013

Year of birth: 1939

Gender: Male

Ethnicity: White, non-Hispanic

Smoking History: Former Smoker

Employment Information

Employer: Fernald

Start date: 1/01/1986

End date: 12/31/1988

Occupation: Chemical Operator – worked with thorium

Bioassay: *In Vivo* Data

Date	Facility	Plant	Th (mg)	Ac-228 (nCi)	Pb-212 (nCi)	Th-232 (nCi)
6/11/1986	MIVRML	9		0.09	0.04	
5/18/1987	MIVRML	9		0.07	-0.04	
6/15/1988	MIVRML	9		0.08	0.05	

Based on DL information below, all in vivo counts are negative, < DL, so only missed thorium dose is assigned (From Attachment B.1):

Bias and DL for Ac-228 and Pb-212 (nCi)

Year	**Pb-212 Bias**	**Pb-212 DL**	**Ac-228 Bias**	**Ac-228 DL**
1986	-0.085	0.128	0.020	0.114
1987	-0.047	0.123	0.008	0.106
1988	0.002	0.181	0.058	0.107

Example DR Evaluated Organs

Cancer	[a]Internal Organ
Lung	Lung
Bone	Bone Surface
Prostate	HNM
[b]Skin, BCC	Skin

a. SRDB Ref ID: 121336 (ORAUT-OTIB-5)
b. BCC=Basal Cell Carcinoma

Missed thorium dose based on chest count measurements:

The DL for Pb-212 for last chest count measurement (06/15/1988) is 0.181 nCi; the MDA is 2 X DL or 0.362 nCi.

The DL for Ac-228 for last chest count measurement (06/15/1988) is 0.107 nCi, the MDA is 2 X DL or 0.214 nCi.

For missed dose calculation, Use ½ of the chest count MDA.

The Pb-212 chest burden was evaluated using the Th-228 biokinetic model in IMBA. This is the intake rate for Th-228.
Assign the intake rate for Th-232 using the triple-separated ratio for Th-228 : Th-232 (0.19 : 1). Since this is triple separated thorium, there is no Ra-228 intake associated with the thorium intake.

The Ac-228 chest burden was evaluated using the Ra-228 biokinetic model in IMBA. This is the intake rate for Ra-228. Because this is unsupported Ra-228, it is not part of the thorium mixture, and only absorption Type M is assessed.

No correction factors were applied in this example; however, it is assumed that correction factors would be applied for non-comp claims since the thorium intake based on a chest count would be a slight underestimate.

Employee 1 - Summary of Derived Intake Estimates (pCi/day)

Radionuclide	Type M	Type S
Th-228	31.548	10.616
Th-232	166.042	55.874
Ra-228 (unsupported)	17.052	Not Applicable

From Attachment F:

Thoron exposure summary

Radionuclide	Time Period	Exposure Rate (WLM/yr)
Rn-220	1986-1988	1.6[a,b]

a. Values are assigned as a constant distribution.
b. Applicable to Lung only (DCAS-TIB-11).

Employee 1 – Material Type Comparison

Organ	Thorium Type M (rem)	Thorium Type S (rem)	Thoron (rem)
Lung	25.651	24.786	29.760
Bone	601.436	17.613	
Prostate	1.396	0.046	
[a]Skin, BCC	1.390	0.044	

a.BCC=Basal Cell Carcinoma

Employee 1 –Summary of Probability of Causation (POC)[a,b]

POC (%)	Lung	Bone	Prostate	Skin
Type M	55.99	92.78	1.28	1.64
Type S	54.08	27.21	0.04	0.05

a. A triangular distribution was assigned in IREP for missed thorium dose based on in vivo counts and a constant distribution was assumed for thoron dose to the lung.
b. Combined POC was not evaluated; organs were independently assessed for comparative purposes.

Employee 2

Cancer Description: Lung (ICD-9: 162); diagnosed 12/31/2013

Bone (ICD-9: 170.2); diagnosed 12/31/2013

Prostate diagnosed (ICD9 185); diagnosed 12/31/2013

BCC, face (ICD-9: 173); diagnosed 12/31/2013

Year of birth: 1939

Gender: Male

Ethnicity: White, non-Hispanic

Smoking History: Former Smoker

Employment Information

Employer: Fernald

Start date: 1/01/1986

End date: 12/31/1988

Occupation: Chemical Operator – worked with thorium

Bioassay: *None*

Because the Chemical Operator worked with thorium, and no bioassay results existed, thorium coworker intakes are assigned, as well as the thoron exposure.

From Attachment C (in development):

Derived Thorium-232 intakes, (pCi/day)

Period	Type M	GSD[a]	Type S	GSD[a]
1986-1988[b]	1.01	7.95	0.220	7.04

a. GSD = Geometric Standard Deviation.
b. These intakes do not represent the finalized values, actual values are in development.

From Attachment F:

Thoron exposure summary

Radionuclide	Time Period	Exposure Rate (WLM/yr)
Rn-220	1986-1988	1.6[a,b]

a. Values are assigned as a constant distribution.
b. Applicable to Lung only (DCAS-TIB-11).

Employee 2 – Material Type Comparison

Organ	Thorium Type M (rem)	Thorium Type S (rem)	Thoron (rem)
Lung	0.153	0.096	29.760
Bone	3.655	0.067	
Prostate	0.008	<0.001	
[a]Skin, BCC	0.008	<0.001	

a. BCC=Basal Cell Carcinoma

Employee 2 –Summary of Probability of Causation[a,b]

POC (%)	Lung	Bone	Prostate	Skin
Type M	40.77	50.94	0.09	0.09

Type S	40.13	1.40	0.00	0.00

a. A GSD was assigned in IREP for thorium coworker doses and a constant distribution was assumed for thoron dose to the lung.
b. Combined POC was not evaluated; organs were independently assessed for comparative purposes.

Employee 3

Cancer Description: Lung (ICD-9: 162); diagnosed 12/31/2013

Bone (ICD-9: 170.2); diagnosed 12/31/2013

Prostate diagnosed (ICD9 185); diagnosed 12/31/2013

BCC, face (ICD-9: 173); diagnosed 12/31/2013

Year of birth: 1939

Gender: Male

Ethnicity: White, non-Hispanic

Smoking History: Former Smoker

Employment Information

Employer: Fernald

Start date: 1/01/1990

End date: 12/31/2000

Occupation: Chemical Operator – worked with thorium

Bioassay: Thorium *BZ air monitoring results (1995-2000), no bioassay for 1990-1994 employment*

Page #	Date	Year	Nuclide	Sol. Class	Resp Type	Corrected Dac-hrs	MDI Dac-Hrs	Dac-hrs	Location

58	12/26/1995	1995	Th-230	W	Full-Face	0.002	0.027	0.1	PILOT PLANT
61	3/30/2000	2000	Th-230	W	Full-Face	0.025	0.025	1.272	BLDG 91A
62	10/11/2000	2000	Th-230	W	Full-Face	0.011	0.029	0.55	GRID 31A
62	12/18/2000	2000	Th-230	W	Full-Face	0.022	0.034	1.121	BLDG 91A
62	12/20/2000	2000	Th-230	W	Full-Face	0.01	0.03	0.506	BLDG 91A
62	12/28/2000	2000	Th-230	W	Full-Face	0.015	0.034	0.761	BLDG 91A
58	1/15/1996	1996	Th-232	W	Full-Face	0.1	0.138	5	PILOT PLANT
59	5/16/1996	1996	Th-232	W	PAPR	0.027	0.01	27	BLDG 13A
59	5/17/1996	1996	Th-232	W	PAPR	0.053	0.008	53	BLDG 13A
61	7/18/2000	2000	BL-13	W	PAPR HEPA	0.002	0.003	2.017	BLDG 13

Because the Chemical Operator did not have any bioassay results during his 1990-1994 employment, thorium doses were assigned based on a thorium intake from air limit calculation of 10% Th-232 DAC for 1990-1994. For 1995-2000, his BZ air monitoring results were used to assign thorium doses.

Inhalation and Ingestion intake rates based on 10% of Th-232 DAC

From Attachment F:

Timeframe	Inhalation Rate	Ingestion Rate

	(dpm/yr)	(dpm/yr)
1990-1994	266.4	5.55

From Attachment E:

Thoron exposure summary

Radionuclide	Time Period	Exposure Rate (WLM/yr)
Rn-220	1990 - 2000	0.5[a]

a. Values are assigned as a constant distribution.
b. Applicable to Lung only (DCAS-TIB-11).

For the 1995-2000 BZ air monitoring results, the corrected DAC-hrs (by radionuclide) and (by year) were summed. The summation of these results were then converted from DAC-hrs to a unit of intake (pCi), and then doses calculated, with the most claimant favorable material type selected. (See also DAC-Hr Conversion workbook and EDAC_BI13_2000 files within Example 3 folder).

Employee 3 – Material Type Comparison

Organ	Thorium Type M (rem)	Thorium Type S (rem)	Thoron (rem)
Lung	0.029	0.140	34.100
Bone	1.535	0.128	
Prostate	0.003	<0.001	
[a]Skin, BCC	0.003	<0.001	

a.BCC=Basal Cell Carcinoma

Employee 3 – Summary of Probability of Causation[a,b]

POC (%)	Lung	Bone	Prostate	Skin

Type M	42.53	3.15	0.000	0.000
Type S	42.60	0.26	0.000	0.000

a. A constant distribution was assigned in IREP for thorium doses based on 10% DAC and for thoron dose to the lung. Positive BZ air monitoring results were assigned as a lognormal distribution with a GSD of 3.

b. Combined POC was not evaluated; organs were independently assessed for comparative purposes.