A COMPREHENSIVE DOSE RECONSTRUCTION METHODOLOGY FOR FORMER ROCKETDYNE/ATOMICS INTERNATIONAL RADIATION WORKERS

John D. Boice, Jr.,*[†] Richard W. Leggett,[‡] Elizabeth Dupree Ellis,[§] Phillip W. Wallace,[§] Michael Mumma,* Sarah S. Cohen,* A. Bertrand Brill,[†] Bandana Chadda,* Bruce B. Boecker,** R. Craig Yoder,[††] and Keith F. Eckerman[‡]

Abstract—**Incomplete radiation exposure histories, inadequate treatment of internally deposited radionuclides, and failure to account for neutron exposures can be important uncertainties in epidemiologic studies of radiation workers. Organ-specific doses from lifetime occupational exposures and radionuclide intakes were estimated for an epidemiologic study of 5,801 Rocketdyne/Atomics International (AI) radiation workers engaged in nuclear technologies between 1948 and 1999. The entire workforce of 46,970 Rocketdyne/AI employees was identified from 35,042 Kardex work histories cards, 26,136 electronic personnel listings, and 14,189 radiation folders containing individual exposure histories. To obtain prior and subsequent occupational exposure information, the roster of all workers was matched against nationwide dosimetry files from the Department of Energy, the Nuclear Regulatory Commission, the Landauer dosimetry company, the U.S. Army, and the U.S. Air Force. Dosimetry files of other worker studies were also accessed. Computation of organ doses from radionuclide intakes was complicated by the diversity of bioassay data collected over a 40-y period (urine and fecal samples, lung counts, whole-body counts, nasal smears, and wound and incident reports) and the variety of radionuclides with documented intake including isotopes of uranium, plutonium, americium, calcium, cesium, cerium, zirconium, thorium, polonium, promethium, iodine, zinc, strontium, and hydrogen (tritium). Over 30,000 individual bioassay measurements, recorded on 11 different bioassay forms, were abstracted. The bioassay data were evaluated using ICRP biokinetic models recommended in current or upcoming ICRP documents (modified for one inhaled material to reflect site-specific information) to estimate annual doses for 16 organs or tissues taking into account time of exposure, type of radionuclide, and excretion patterns. Detailed internal exposure scenarios were developed and annual internal doses were derived on a case-by-case basis for workers with committed equivalent doses indicated by screening criteria to be greater than 10 mSv to the organ with the highest internal dose. Overall, 5,801 workers were monitored for radiation at Rocketdyne/AI: 5,743 for external exposure and 2,232 for internal intakes of radionuclides; 41,169 workers were not monitored for radiation. The mean cumulative external dose based on Rocketdyne/AI records alone was 10.0 mSv, and the dose distribution was highly skewed with most workers experiencing low cumulative doses and only a few with high doses (maximum 500 mSv). Only 45 workers received greater than 200 mSv while employed at Rocketdyne/AI. However, nearly 32% (or 1,833) of the Rocketdyne/AI workers had been monitored for radiation at other nuclear facilities and incorporation of these doses increased the mean dose to 13.5 mSv (maximum 1,005 mSv) and the number of workers with >200 mSv to 69. For a small number of workers (*n* = 292), lung doses from internal radionuclide intakes were relatively high (mean 106 mSv; maximum 3,560 mSv) and increased the overall population mean dose to 19.0 mSv and the number of workers with lung dose >200 mSv to 109. Nearly 10% of the radiation workers (584) were monitored for neutron exposures (mean 1.2 mSv) at Rocketdyne/AI, and another 2% were monitored for neutron exposures elsewhere. Interestingly, 1,477 workers not monitored for radiation at Rocketdyne/AI (3.6%) were found to have worn dosimeters at other nuclear facilities (mean external dose of 2.6 mSv, maximum 188 mSv). Without considering all sources of occupational exposure, an incorrect characterization of worker exposure would have occurred with the potential to bias epidemiologic results. For these pioneering workers in the nuclear industry, 26.5% of their total occupational dose (collective dose) was received at other facilities both prior to and after employment at Rocketdyne/AI. In addition, a small number of workers monitored for internal radionuclides contributed disproportionately to the number of workers with high lung doses. Although nearly 12% of radiation workers had been monitored for neutron exposures during their career, the cumulative dose levels were small in comparison with other external and internal exposure. Risk estimates based on nuclear worker data must be interpreted cautiously if internally deposited radionuclides and occupational doses received elsewhere are not considered.**

Health Phys. 90(5):409–430; 2006

Key words: dose assessment; exposure, occupational; epidemiology; nuclear workers

---

* International Epidemiology Institute, 1455 Research Blvd., Suite 550, Rockville, MD 20850; [†] Vanderbilt University Medical School and Vanderbilt-Ingram Cancer Center, Nashville, TN; [‡] Oak Ridge National Laboratory, Oak Ridge, TN; [§] Oak Ridge Associated Universities, Oak Ridge, TN; ** Lovelace Respiratory Research Institute, Albuquerque, NM; [††] Landauer, Inc., Glenwood, IL.

For correspondence or reprints contact: John D. Boice, Jr., International Epidemiology Institute, 1455 Research Blvd., Suite 550, Rockville, MD 20850, or email at john.boice@vanderbilt.edu.

(*Manuscript received* 18 *October* 2004; *revised manuscript received* 13 *July* 2005, *accepted* 11 *November* 2005)

0017-9078/06/0

Copyright © 2006 Health Physics Society

INTRODUCTION

Epidemiologic studies of radiation workers are conducted to gain direct knowledge of low dose and low dose-rate exposures (Gilbert et al. 1993a and b; Frome et al. 1997; Cardis et al. 1995, 2005; Muirhead et al. 1999; Omar et al. 1999; Gilbert 2001; Sont et al. 2001; Iwasaki et al. 2003; Boice 2006). Such studies can also validate current radiation risk estimates based on higher doses delivered at higher dose rates. Inherent limitations of occupational studies include relatively small numbers of workers at individual facilities and relatively low cumulative doses even when several studies are combined (Gilbert et al. 1993b; Cardis et al. 1995, 2005; UNSCEAR 2000). Sample size and exposure levels affect statistical power, i.e., the ability of a study to detect an effect given that there is one. However, there are other sources of uncertainty that can distort study findings. Although personnel monitoring devices and bioassay measurements provide estimates of radiation dose in ways far superior than possible for chemical or other agents found in the workplace, they are nonetheless subject to random error and to systematic biases (Gilbert and Fix 1995; Gilbert et al. 1996; Gilbert 1998; Daniels et al. 2005; Daniels and Schubauer-Berigan 2005). Random error in the measurement of dose is independent across workers and tends to reduce the power for detecting effects. Systematic error or bias can lead to spurious results. Systematic biases can include inadequate collection of prior or subsequent radiation work histories, inadequate treatment of the intake of radionuclides, and underestimation of neutron exposures. Other sources of possible bias include medical radiation procedures, natural background radiation, and even conventions in recording radiation dose, e.g., for doses below a minimum detectable level (MDL) of the measurement device setting the dose to either zero or to the MDL, or assigning a value for missing dose as the maximum allowed by regulation during the reporting period. Measurement uncertainties include those associated with differences in photon energy, exposure geometry, and type of dosimeter.

In this paper we address the magnitude of several sources of systematic bias within the context of a comprehensive dose reconstruction study of Rocketdyne/Atomics International (AI) workers (Fig. 1). Three sources of potential bias will be evaluated: radiation exposures received elsewhere, internal intakes of radionuclides, and neutron exposures. Inadequate or improper treatment of these exposures would tend to underestimate organ doses and overestimate derived risk per unit dose. This dose reconstruction program was conducted in support of an epidemiologic study to identify health effects on Rocketdyne/AI workers exposed to radiation (Boice et al.)[‡‡] and not for support of compensability decisions (Office of Workers' Compensation Programs 2005; NRC 2003, 2005). The paper does not focus on all sources of uncertainty but on the three mentioned for which serious bias could result if not handled properly in the context of the current study.

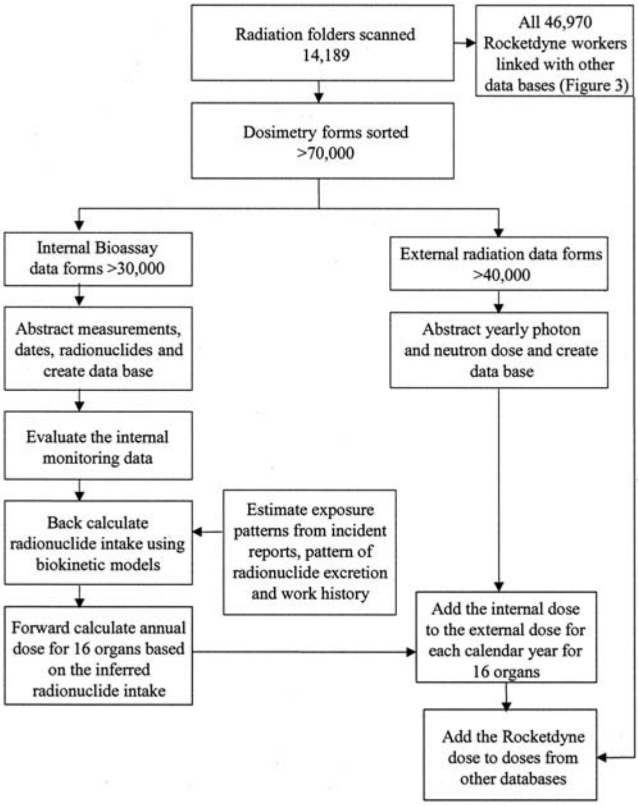


Fig. 1. Flowchart of procedure for radiation dose determination for Rocketdyne/AI workers.

Since 1996, Rocketdyne had been owned by The Boeing Company and was sold in 2005 to Pratt & Whitney. Previous corporate owners were Rockwell International (1973–1996), North American Rockwell (1967–1973), and North American Aviation (1928–1967). North American Aviation established Rocketdyne as a separate division in 1955, and Atomics International was also established as a division that same year. Atomics International merged with Rocketdyne in 1984. Throughout this paper, "radiation workers at Rocketdyne" is meant to include all radiation workers at the Santa Susana Field Laboratory (SSFL) and nearby facilities in California regardless of corporate ownership at the time of occupational exposure to radiation.

Between 1948 and 1999, thousands of Rocketdyne/Atomics International workers were involved in a wide

---

[‡‡] Boice JD, Jr, Cohen SS, Mumma MT, Ellis ED, Eckerman KF, Leggett RW, Boecker BB, Brill AB, Henderson BE. Mortality among radiation workers at Rocketdyne (Atomics International), 1948–1999.

range of activities such as sodium-cooled breeder reactor technology, uranium fuel fabrication, spent fuel evaluation, radiography, hot lab chemistry, plutonium fuel fabrication and storage of nuclear material. During the 52 years covered by the study, 5,801 workers were monitored for external or internal radiation: 3,569 external only, 58 internal only, and 2,174 both internal and external (Table 1). Bioassay measurements of radioactivity in urine and feces and whole-body and lung counts were recorded for workers. Monitored radionuclides included isotopes of uranium, plutonium, americium, thorium, polonium, cesium, cerium, calcium, iodine, zinc, zirconium, promethium, strontium, and hydrogen (tritium).

A number of workers were employed at other nuclear facilities before being hired by Rocketdyne/AI, and many also were subsequently employed in radiation occupations after leaving Rocketdyne/AI. To better characterize the lifetime dose received by the workforce from all sources, attempts were made to obtain additional data through record linkage with dosimetry files available from the Department of Energy, the Nuclear Regulatory Commission, the Landauer dosimetry company, the U.S. military services, and nine individual nuclear facilities or prior study databases. To be included in this study, workers had to have been monitored for radiation at the SSFL or nearby facilities in California. The study received human subjects research approval from Vanderbilt University, The Boeing Company, and the Oak Ridge Site-Wide Institutional Review Boards.

METHODS

The approach for obtaining lifetime career doses and internal radiation doses to specific organs involved data imaging, abstraction of internal monitoring documents, obtaining external radiation exposure histories at Rocketdyne/AI, record linkage with nationwide and facility-specific dosimetry files for external dosimetry outside of Rocketdyne/AI, and internal dosimetry and biokinetic modeling.

Data imaging

The goal of the imaging and abstraction process was to create an electronic file for use in an organ dose reconstruction scheme. Internal and external ionizing radiation monitoring data from hard-copy records for the employees at SSFL and other nearby Rocketdyne facilities were evaluated. Because of the wealth of information available in the radiation worker folders, as well as the

Table 1. Demographic and job characteristics for eligible workers who were monitored for radiation at Rocketdyne (n = 5,801).

Characteristic		*n*	%	Characteristic		*n*	%
Sex	Male	5,335	92.0	Years of employment	0.5–<1	215	3.7
	Female	466	8.0		1–4	1,730	29.8
					5–9	1,205	20.8
					10–14	939	16.2
Race	White	4,695	80.9		15–19	579	10.0
	Nonwhite	340	5.9		≥20	748	12.9
	Missing	766	13.2		Unk/Miss/Incorrect	385	6.6
Year of birth	<1920	937	16.2	Radiation monitoring at Rocketdyne	External only	3,569	61.5
	1920–1929	1,670	28.8		External and internal	2,174	37.5
	1930–1939	1,701	29.3		Internal only	58	1.0
	1940–1949	769	13.3				
	1950–1959	534	9.2	Sources of radiation dosimetry information	Rocketdyne	5,801	100.0
	≥1960	190	3.3		Landauer	1,333	23.0
					Dept of Energy	1,044	18.0
					Nuclear Reg Comm	1,038	17.9
Year of hire	<1948	98	1.7		U.S. Air Force	34	0.6
	1948–1959	2,471	42.6		U.S. Army	57	1.0
	1960–1969	1,963	33.8		U.S. Navy	26	0.4
	1970–1979	607	10.5		Individual sources	64	1.1
	1980–1989	595	10.3				
	≥1990	67	1.2	Number of sources providing radiation dosimetry information	1 (Rocketdyne only)	3,212	55.4
					2	1,713	29.5
					3	779	13.4
					4	89	1.5
Year of termination	<1960	319	5.5		5	8	0.1
	1960–1969	2,370	40.9				
	1970–1979	924	15.9	Vital status as of 12/31/1999	Alive	4,186	72.2
	1980–1989	844	14.5		Dead	1,468	25.3
	1990–1999	817	14.1		Died outside US	5	0.1
	Active (12/31/1999)	527	9.1		Lost to follow-up	142	2.4

complexity of the bioassay report forms used over the years, it was decided to scan and image all the folder information into a searchable database. Among the 54,384 employees initially identified, 14,189 were potential radiation workers based on having a radiation folder.

Administrative practices at the time required that each employee be issued a "radiation folder," whether or not he or she would ever be monitored for radiation or actually receive occupational exposure to radiation. The folders for every potential radiation worker were scanned and indexed by name, social security number, worker serial numbers, date of birth, and date of hire. There were 7,204 workers subsequently excluded from the cohort when it was established because they were not occupationally exposed to radiation. These workers were excluded because they were never monitored for radiation exposure and had no dosimetry information in their folders. There were also 350 workers excluded because they worked for less than 6 months, and 524 workers because of insufficient identifying information. All of the scanned images of the radiation monitoring records were prescreened to identify those data folders that contained bioassay data.

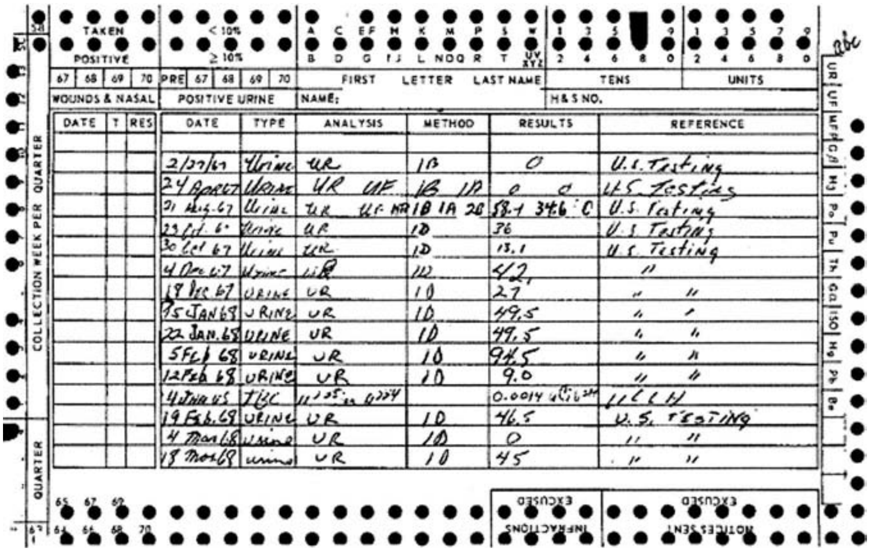
Abstraction of internal monitoring documents

The work proceeded as follows: documentation of data flow and procedures, prescreening the scanned images, data entry, quality assurance, and quality control.

Documentation of data flow and procedures. All activities associated with prescreening of the imaged files and construction of the electronic file containing the internal radiation monitoring data from the scanned images of the hard-copy records were documented.

Prescreening the scanned images. The radiation monitoring records were scanned in batches according to the likelihood of radiation exposure based on length and calendar year of employment, facility of employment, and information available from the prior investigation (Ritz et al. 1999). Workers most likely to have the highest exposure to radionuclide intakes were scanned first to assure that proper effort was made to reconstruct these rather complex dosimetry situations. As a result of the initial records review, 11 different types of records containing bioassay data were identified. Fig. 2 is an example of a bioassay data form used after 1962.

Because of the number and variations in the layout of the documents to be entered, speed and accuracy in the entry process were facilitated by grouping like documents together. A folder was created on the desktop for each of the 11 types of internal radiation monitoring records. Each scanned image in the worker's radiation folder was then evaluated, and a copy of the image was placed in the appropriate folder. A unique number assigned to each image as it was scanned was used to link the record to the correct worker. The few documents of interest with a different format from the 11 common



WOUNDS & NASAL | POSITIVE URINE | NAME: | H&S NO.

DATE	T	RES	DATE	TYPE	ANALYSIS	METHOD	RESULTS	REFERENCE
			2/27/67	Urine	UR	1B	0	U.S. Testing
			24 Apr 67	Urine	UR UF	1B 1A	0 0	U.S. Testing
			21 Aug. 67	Urine	UR UF MFP	1B 1A 2B	58.4 34.6 0	U.S. Testing
			23 Oct. 6[illegible]	Urine	UR	1D	36	U.S. Testing
			30 Oct 67	Urine	UR	1D	13.1	U.S. Testing
			4 Dec 67	Urine	UR	1D	42	"
			18 Dec 67	URINE	UR	1D	27	" "
			15 JAN 68	URINE	UR	1D	49.5	" "
			22 JAN. 68	URINE	UR	1D	49.5	" "
			5 Feb 68	URINE	UR	1D	94.5	" "
			12 Feb 68	URINE	UR	1D	9.0	" "
			4 Jan [illegible]	TBC	U235 in [illegible]		0.0014 μCi U235	[illegible]
			19 Feb. 68	URINE	UR	1D	46.5	U.S. TESTING
			4 Mar 68	urine	UR	1D	0	" "
			18 Mar 68	urine	UR	1D	45	" "

Fig. 2. Master record for internal monitoring data, starting about 1963. Date is day of sample collection. In this example, types of measurements were urinalyses for uranium (radiometric = UR, code 1B; fluoroscopic = UF, code 1A) and mixed fission products (MFP, code 2B), and total-body counting of ^{235}U (TBC). For a urine sample collected on 21 Aug 67, for example, results for UR, UF, and MFP are 58.4 (dpm d^{-1}), 34.6 (μg d^{-1}), and 0 (dpm d^{-1}), respectively, assuming a daily urine volume of 1,500 mL. Some cards in the 1950's and early 1960's used a "+/0" notation system to indicate positive and negative bioassays. Numeric values were then provided on bioassay documents in the folder.

document types were placed in a separate folder to be data entered by the supervisor of the data entry clerks.

Data entry. Data entry was accomplished using a dual monitor approach with one monitor used for viewing the scanned image and the second monitor used for inputting the data. The result was a paperless process designed to increase productivity and reduce data entry cost. MS Access (Microsoft Corporation, One Microsoft Way, Redmond, WA 98052-6399) was used for data entry. The folders of images created during the prescreening were used to access the records pertaining to the internal radiation monitoring of workers. A data entry form was developed for each document type. Because of the variety of document types and the number of vendors used, all documents in a given folder (and of a given type) were entered together. Over 30,000 internal radiation monitoring records were processed.

Quality assurance. Quality assurance (QA) procedures were established to confirm the accuracy of the data file created and to promote cost efficiency and timeliness. These procedures verified both the completeness of the prescreening of the records and the accuracy of the data entry. A sampling plan was developed to specify sample size and associated acceptance criteria based on statistical standards. The basic sampling unit was an entire record that was evaluated as either defective or not defective. Clear operational definitions were developed to insure that errors were assessed consistently and precisely.

When data entry on a new form was started, it was closely monitored to assure that the data entry clerks understood clearly the instructions for entry and had opportunities to ask questions. There was also real time clean up on mismatched records, i.e., when the record in the scanned file was incorrectly assigned to a specific worker. For example, when a scanned file was found that contained records for more than one person or the wrong person, the linkage was changed to the correct worker. These mismatches were identified by both the data administrator and the data entry clerk.

Quality controls. After data entry and verification, quality control (QC) activities were carried out on the second electronic file created from the initial electronic file. This second file was used to perform several edit checks. The first compared the range of dates in the monitoring data against the hire and termination dates for the worker available from Kardex work histories or electronic personnel listings. The second checked the completeness of the individual numeric results from the bioassay sample against the "+/0" values recorded on the summary cards for the time period 1 January 1961 through 31 December 1967. The "+/0" designators on the summary cards indicated the availability of numeric bioassay results recorded on separate documents in the worker's radiation folder and were only used for the period 1961–1967. After that, the numeric values were recorded on the summary card.

Results of processing internal monitoring documents. There were 952 workers included in the internal dosimetry initial selection, i.e., those who likely received the highest intakes of radionuclides based on job location, calendar year, and available Rocketdyne bioassay data. An MS Access database containing a total of 27,023 records of internal radiation monitoring data was compiled from the scanned images of interest for these workers. A copy of this file was provided to the internal dosimetrists for use in reconstructing doses for these workers.

In addition, we visually reviewed over 200,000 records within the 14,189 worker folders for any indication of either internal or external dosimetry. Subsequently, 1,280 additional workers were identified as monitored for possible intakes of radionuclides, although the bioassay data indicated no more than minimal levels of detection for the assay employed. Overall, 2,232 workers were determined to have worked in areas with the potential for radionuclide intakes and were so monitored.

Finally, to supplement the information available in the scanned folders of radiation workers, we also evaluated any incident reports of potential unusual exposures or wounds occurring in a controlled area as well as dosimetry workups made at an individual's personal request. Complete dosimetry assessments had been performed on 410 workers by the Rocketdyne health physics staff based on worker request or for compensation considerations.

Obtaining external radiation exposure histories at Rocketdyne/AI

The overall plan was to obtain a complete career history of radiation exposure for each worker, including doses prior, during, and after employment at Rocketdyne/AI. All 14,189 Rocketdyne/AI radiation folders were reviewed, and those with evidence of radiation monitoring were selected. Because of an administrative policy to issue a radiation folder to all new employees regardless of their potential for radiation exposure monitoring, 7,204 workers were excluded as not being radiation workers. These excluded workers had never worked in an area requiring a radiation-monitoring device and they had no dosimetry information in their folders. Kardex job histories were sought to identify any workers without monitoring information, and discussions with former employees were held to confirm that there was no group of non-monitored employees who consistently worked in radiation areas. Similar to what was done for the internal radiation exposure, external radiation records were selected and sorted by type of form/vendor to facilitate data entry. Entry into both MS Excel and MS Access databases included name, social security number, calendar year of exposure, photon radiation dose for that calendar year, neutron dose for that calendar year, and an indicator that the dose was received prior to Rocketdyne employment, during employment (whether onsite or offsite), or subsequent to Rocketdyne employment. All dosimetry data after 1990 had been computerized and were accessible directly. There were 5,743 workers identified as having been monitored for external radiation at Rocketdyne facilities.

Care was taken to exclude individuals who were working at Rocketdyne as contractors. Contract workers could be identified from a computerized database of 4,675 contract workers. The contractors were not Rocketdyne employees, did not have work histories, did not have worker serial numbers, and did not have complete dosimetry information. Because of the various exclusion criteria and the lack of identifying information for many workers, it was not possible to determine the actual number of contract workers excluded. At least several hundred contract workers were excluded, but the actual number could have been much more.

Record linkage with nationwide and facility-specific dosimetry files for external radiation outside of Rocketdyne

Anecdotal information combined with evidence in a number of dosimetry files suggested that a significant number of Rocketdyne/AI workers had been exposed to ionizing radiation at other facilities, both before and after working at Rocketdyne. For an accurate assessment of the risk from occupational radiation, it was essential that complete lifetime doses be determined. External radiation exposure records were obtained from a variety of sources in an attempt to characterize lifetime occupational exposures for all workers. The dosimetry data found in the Rocketdyne/AI radiation folders, which formed the basis of the radiation worker database, were then supplemented with dosimetry information obtained from the Landauer dosimetry company, the Nuclear Regulatory Commission, the Department of Energy, and the military services (e.g., the U.S. Army) (Muirhead et al. 1996). In addition, nuclear facilities where a worker was employed prior to joining Rocketdyne or transferred to after employment with Rocketdyne/AI were identified and dosimetry information obtained (Gilbert et al. 1993a; Fry et al. 1996; Frome et al. 1997; Dupree-Ellis et al. 2000).

Permissions were sought to access various national dosimetry databases using name, social security number, and date of birth as matching variables. The Nuclear Regulatory Commission REIRS files (Radiation Exposure Information and Reporting System) contained exposure information by calendar year for workers who terminated employment at any of the NRC licensee facilities. The Department of Energy allowed access to various databases including the REMS (Radiation Exposure Monitoring System) files. The Landauer dosimetry company has computerized records of their clients beginning in 1977 and hard copy records back to 1953. Landauer was the major source of additional dosimetry from non-nuclear facilities, e.g., medical or industrial radiography. The U.S. Army and U.S. Air Force had computerized dosimetry records beginning as early as 1959 and 1962, respectively. Other sources of dosimetry information included investigators of other worker studies who were asked to match their dosimetry files against our study roster. In total, radiation dosimetry was obtained from five major national databases, including 32 different nuclear facilities.

Matching the 5,801 Rocketdyne/AI radiation worker files with the external dosimetry databases identified 1,833 workers (nearly 32% of all radiation workers) who had been monitored for radiation exposure at other facilities. Interestingly, matching the 41,169 Rocketdyne non-radiation worker files with the same databases also revealed that 1,477 (3.6%) of these workers had been monitored for radiation doses at non-Rocketdyne facilities.

Table 1 and Fig. 3 present the number of dosimetry sources and number of workers for whom dosimetry information was obtained. Over 36% of all radiation workers were employed at facilities other than Rocketdyne, and some workers had been employed at as many as five different facilities. By far, the Hanford site had employed more Rocketdyne employees (1,194) than any other installation, consistent with the fact that Rockwell International was the third manager of the Hanford site after Dupont and General Electric. Other frequent places of employment included the Idaho National Engineering Laboratory (INEL; 237), Rocky Flats (160), the Nevada Test Site (103), Los Alamos National Laboratory (92), the Oak Ridge site (95), Argonne National Laboratory (74), the U.S. Air Force (152), and the U.S. Army (152). Access to U.S. Navy dosimetry records was not obtained, but information in the Rocketdyne radiation folders was found for 26 workers who had been previously employed in the Nuclear Navy (mean dose 8.0 mSv; range 0–45.3

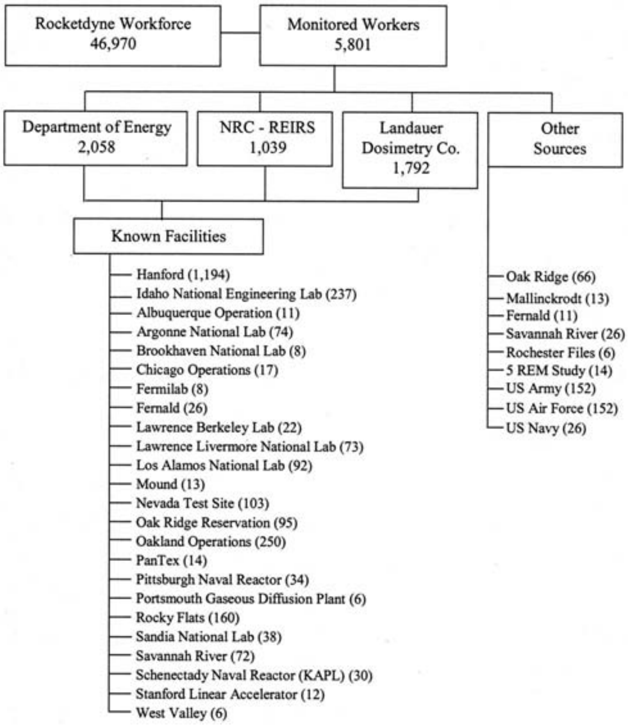


Fig. 3. Sources of radiation exposure histories.

mSv). Throughout this manuscript we use the term "dose" interchangeably with "equivalent dose" although "equivalent dose" is technically correct when units of mSv are used.

Dose information was available from seven overlapping sources (Fig. 3, Table 2). Care was taken to assure that only non-overlapping dosimetry information was incorporated into the analyses. Occasionally, calendar year exposures were not available, and for such instances the cumulative dose, or termination dose, was recorded in the calendar year in which it was reported. These combinations occurred primarily for early doses obtained prior to employment at Rocketdyne/Atomics International and thus will have little impact on the exposure lagging analyses, i.e., even a 10-y lag period would be unlikely to result in any of these exposures being excluded. The major source of radiation exposure histories came from the Rocketdyne/AI files, which also included documentation of prior radiation doses received by over 400 workers. Other sources of information included the Landauer dosimetry company (n = 1,792), which was the major vendor providing dosimetry services for Rocketdyne/AI over the years, the Department of Energy (n = 2,058), which oversaw the Hanford site and other national laboratories where Rocketdyne/Rockwell International had management responsibilities, and the Nuclear Regulatory Commission (n = 1,039). Mean doses are presented in Table 2 by source of radiation history. The mean and collective doses for workers monitored for radiation at Rocketdyne increased by 35% when the doses received elsewhere were included, i.e., from 10.0 mSv to 13.5 mSv and from 57.4 person-Sv to 77.6 person-Sv. Of the 1,833 workers who had been monitored for radiation other than at Rocketdyne/AI, 604 (or 10%) had greater occupational exposures elsewhere than received at Rocketdyne. Also as noted, 1,477 workers who were not monitored for radiation at Rocketdyne were monitored elsewhere, although their mean dose was low (2.6 mSv).

Neutrons. There were 584 radiation workers (10%) who had been monitored for neutron exposures at Rocketdyne/AI and an additional 81 radiation workers who were monitored for neutrons at other facilities: 617 had <5 mSv, 35 between 5–10 mSv, and 13 had between 10–60 mSv (mean 1.2 mSv; max 55.8 mSv). It was presumed that quality factors of 10 for fast neutrons and 3 for slow neutrons had been used to reflect the relative biological effectiveness of neutrons in comparison with photons (ICRP 1991). These neutron doses were added to the other external and internal doses received by each worker. The contribution of neutron doses to total dose for the 665 workers monitored for neutron exposures, however, was small and less than 3% of the total external photon dose they received. The contribution of neutron dose to the collective dose from all external exposures was accordingly small and only 0.8 person-Sv or <0.1%.

Examples of worker doses received elsewhere. Just over 400 workers had a record of prior radiation work that was found in the Rocketdyne/AI folders; over 500 additional workers were found through record linkage to have had prior radiation exposure; and over 1,200 workers had been found through record linkage to have left Rocketdyne and were monitored for radiation elsewhere. Below are several examples where incomplete knowledge of occupational radiation received elsewhere would have led to serious underestimation of a worker's exposure.

- One worker employed at Rocketdyne from 1961 to 1964 had received 42.9 mSv while so employed; he had come from INEL with 131.3 mSv and received 10.8 mSv after leaving Rocketdyne and returning to INEL for a total career dose of 185.0 mSv;
- Another worker was employed at Rocketdyne/AI between 1962 and 1967 and received 11.2 mSv. He left Rocketdyne for Hanford and received an additional 125.3 mSv for a total career dose of 136.5 mSv; and
- Another worker was employed at Rocketdyne/AI between 1960 and 1961 and received 3.8 mSv total radiation dose. After leaving, he worked at the Idaho

Field Site and at Argonne National Laboratory where he received an additional 157.1 mSv for a total career dose of 160.9 mSv.

There were also 1,477 workers who were not monitored for radiation at Rocketdyne/AI but were monitored elsewhere. Several examples are given below.

- One worker who began work at Rocketdyne in 1979 but was not monitored for radiation during his employment had received 186 mSv prior to Rocketdyne at INEL; and
- Another worker who left Rocketdyne in 1969 without being monitored for radiation was subsequently monitored at the Hanford site and received 188 mSv.

Internal dosimetry and biokinetic models

Assignment of doses from internally deposited radionuclides. Annual doses from internally deposited radionuclides were estimated in cases where intakes were indicated by positive bioassay data, in vivo lung counts, or incident reports. Screening criteria were developed to reduce time-consuming analyses of relatively low intakes unlikely to be meaningful with regard to the goals of the epidemiological study. The screening criteria were described in terms of total intake of specific radionuclides but were based on the primary criterion that projected lifetime equivalent doses from all intakes combined were less than 10 mSv to any tissue. To implement this, biokinetic models were used to develop intake levels specific to different forms of radionuclides that produce a 50-y equivalent dose of at least 10 mSv to the tissue receiving the highest dose. Annual doses from internally deposited radionuclides were calculated for those workers (292) whose intakes met this criterion.

Internal monitoring data were found for 2,232 workers. These consisted primarily of measurements of radionuclides in urine, supplemented in many cases with fecal measurements and external lung counts. For workers assigned to areas with a relatively high potential for internal exposure, urine samples generally were collected at regular intervals. Sampling typically was on a quarterly basis but was more frequent if elevated exposure was suspected. Follow-up measurements generally were made if elevated internal exposure was detected.

In vivo lung counting was performed in many cases involving suspected inhalation of enriched uranium and in some cases involving suspected exposure to other radionuclides. Measurements of uranium in the lungs were generally reported as a mass of ^{235}U. Conversion to activity in the lungs was based on information or assumptions regarding the level of ^{235}U enrichment of the uranium to which the worker was exposed. Over the years the uranium handled by the Rocketdyne/AI workers varied in enrichment from a few percent up to about 93%.

Intake estimates for workers sometimes were inferred or adjusted on the basis of data for coworkers with apparently similar exposures but more extensive monitoring data. For example, if nasal smears suggested that two workers had similar intakes during an incident and follow-up bioassay data were available for only one of the workers, then those data were assumed to apply to the other worker as well. Such use of surrogate data may often overestimate intake because health physicists may have based decisions regarding follow-up of individual

Table 2. Number of workers and mean external dose (mSv) by source of radiation history and whether or not workers were monitored for radiation while at Rocketdyne.

	Monitored for external radiation at Rocketdyne[a]					
	Yes		No		Total	
Sources of dose information	No.	Mean dose (mSv)	No.	Mean dose (mSv)	No.	Mean dose (mSv)
Rocketdyne files	5,743	10.0	0	—	5,743	10.0
Landauer	1,333	21.7	459	2.7	1,792	16.9
DOE	1,042	8.3	1,016	2.7	2,058	5.5
NRC	1,037	18.0	2	3.0	1,039	17.9
U.S. Army	57	0.9	95	1.1	152	1.0
U.S. Air Force	34	1.9	118	0.3	152	0.7
U.S. Navy[b]	26	8.0	0	—	26	8.0
Other sources	64	6.2	2	0	66	6.0
Total, unique workers	5,751[c]	13.5	1,477	2.6	7,228	11.3

[a] $N = 58$ workers who are in the Rocketdyne Radiation Cohort but were only monitored for internal radiation are not included in this tabulation.

[b] Doses from the U.S. Navy are incomplete because no linkage was made of the entire cohort to Navy records. However, doses received while in the Navy were obtained for some Rocketdyne workers from correspondence documents in the Rocketdyne radiation folders.

[c] $N = 8$ workers who were only monitored for internal radiation while at Rocketdyne were found to have received external radiation prior to work at Rocketdyne and thus are included in this tabulation.

workers on more information than appears in the workers' folders. On the other hand, use of surrogate data is supported by a number of comparisons showing that groups of workers involved in the same incidents often showed similar urinary excretion of radionuclides over an extended period.

Radionuclides addressed. Radionuclides listed in the bioassay records of the Rocketdyne/AI workers include isotopes of uranium, strontium, cesium, plutonium, americium, zirconium, zinc, thorium, polonium, cerium, promethium, calcium, iodine, and hydrogen (tritium). Those radionuclides resulting in highest estimated internal doses at this site are listed in Table 3. Reported data sometimes were not specific to radionuclides but were given as total activity of mixed fission products, gross alpha, gross beta, or other non-specific terms. In such cases, the activity generally was assigned to the dosimetrically dominant radionuclide among those likely to be present in significant quantities. The most frequent use of such a "surrogate radionuclide" involved the assumption that activity reported as "mixed fission products" consisted entirely of the long-lived bone seeker ^{90}Sr. In most but not all such cases, this dosimetrically cautious assumption produced integrated dose estimates lower than the screening level of 10 mSv described earlier.

Models used to interpret bioassay data

Three general types of biokinetic models. Reconstruction of doses from bioassay data was based on biokinetic models that predict the time-dependent distribution and excretion of radionuclides deposited in the human body. The biokinetic models are of three main types: a generic respiratory tract model that describes the deposition and retention of inhaled material in the respiratory tract and its subsequent clearance to blood or to the GI tract; a generic GI tract model that describes the movement of swallowed or endogenously secreted material through the stomach and intestines and, together with element-specific absorption fractions, its absorption to blood; and element-specific systemic biokinetic models that describe the time-dependent distribution and excretion of radionuclides after their absorption into blood.

Respiratory tract model. Intakes were assumed to be by inhalation unless there was reasonably good evidence of intake through ingestion or a puncture wound. The structure of the ICRP's current respiratory model (ICRP 1994a) was applied to all inhalation cases. For each case, an "absorption type" was assigned to the inhaled radionuclide on the basis of best available information, such as records of the nature of the work and the material being handled, the pattern of excretion of the radionuclide over time, or the rate of decline of activity in the lungs. Four absorption types for inhaled particulates were considered: Type F, Type M, or Type S as defined by the ICRP (ICRP 1994a, 1994b), or Type "Modified S," which was developed by the investigators specifically for application to uranium aluminide.

Type F, Type M, and Type S, respectively, are generic descriptions of rates and directions of transfer of highly soluble, moderately soluble, and highly insoluble material in the respiratory tract. They are referred to as "absorption types" because the rate of absorption of an inhaled radionuclide from the respiratory tract to blood generally increases with the rate of dissolution of the inhaled carrier in the tract.

Type F was applied to nearly all cases involving inhalation of strontium, cesium, calcium, and unspecified mixed fission products presumed to consist of ^{90}Sr or, in some cases, a mixture of ^{90}Sr and ^{137}Cs. Application of Type F to these cases was based mainly on recommendations of the ICRP and, as illustrated in Fig. 4, is generally supported by comparisons of model predictions with excretion data in cases with detailed follow-up data.

Type M was used as the default absorption type for isotopes of uranium, plutonium, thorium, cerium, promethium, and polonium. Application of Type M to these radionuclides is consistent with recommendations of the ICRP and, as illustrated in Fig. 5, is generally supported by comparisons of model predictions and urinary excretion data in cases where workers exposed to these radionuclides were followed for an extended period.

Special parameter values were developed for a form of uranium called uranium aluminide that showed much different initial behavior in the respiratory tract than predicted by parameter values for Type M material. Beginning in 1966, relatively high internal exposures to uranium sometimes occurred in the "powder room" at the De Soto facility, where large quantities of uranium aluminide were handled. Bioassay data for powder-room workers generally are not consistent with model predictions based on any of the standard absorption types addressed by the ICRP. This is illustrated in Fig. 6, where urinary excretion data for a worker are compared with model predictions for Type M or Type S material based on air monitoring data. Curves for Type M or Type S reflect the assumed intake pattern. In contrast to predictions for these two absorption types, uranium aluminide appeared to have a biphasic pattern of removal from the lungs. As inferred from changes with time in the urinary excretion rate, there was initially little dissolution of inhaled particles, but the material presumably broke

Table 3. Internally deposited radionuclides resulting in the highest internal dose estimates for Rocketdyne/AI workers.[a]

Radionuclide	Comments
^{234}U, ^{235}U, ^{238}U	Alpha emitters. Assumed to be moderately soluble in lungs except for U aluminide, which is initially insoluble. Absorbed U mainly excreted in urine but some deposition in bone, kidneys, and other tissues, with tenacious retention in bone.
^{239}Pu	Alpha emitter. Assumed to be moderately soluble in lungs when the compound is not specified. Absorbed Pu divides mainly between bone and liver with ~10% distributed to other tissues. Extremely slow removal of absorbed Pu from body.
^{90}Sr	Usually relatively soluble in lungs. Absorbed Sr follows calcium and deposits largely in bone, where a portion is retained for many years. For dosimetric purposes, ^{90}Sr frequently was used as a surrogate for undetermined mixtures of ^{90}Sr, ^{137}Cs, and other fission products, i.e., for activity reported as mixed fission products (MFP).
^{232}Th	Alpha emitter. Assumed to be moderately soluble in lungs when the compound is not specified. Systemic biokinetics broadly similar to Pu but higher bone deposition and lower liver deposition than Pu. Gives rise to chain of radionuclides that migrate from parent and deliver much of the total dose.
^{210}Po	Alpha emitter. Usually moderately soluble in lungs. Absorbed Po concentrates mainly in liver, kidneys, spleen, and bone marrow and is eliminated from body over a period of months.
^{241}Am	Alpha emitter. Assumed to be moderately soluble in lungs. Biokinetics similar but not identical to Pu; e.g., Am has slightly higher excretion rate than Pu.
^{144}Ce	Assumed to be moderately soluble in lungs. Biokinetics broadly similar to ^{239}Pu, but dose per unit intake much lower for ^{144}Ce than ^{239}Pu due to shorter half-life of ^{144}Ce and lack of alpha emissions.

[a] Radionuclides listed in approximate decreasing order of importance with regard to internal doses estimated for this site. Evidence of internal exposure was also found for ^{137}Cs, ^{147}Pm, ^{131}I, ^{45}Ca, ^{3}H, and other radionuclides.

down in the lungs over a few months and subsequently was excreted at a rate consistent with moderately soluble material.

This pattern of behavior is consistent with the following theory based on observed properties of uranium-aluminum intermetallic compounds prepared by different techniques (Le Claire and Bear 1956; Buddery et al. 1964; Giles and Tavender 1967; Bland 1968; Subramanyam et al. 1985). Uranium is not distributed completely uniformly in the preparation but may exist as "islands" of unreacted uranium. These islands are seen on microscopic examination as blisters that grow as the underlying uranium is oxidized. The oxidation of uranium islands may begin slowly but may accelerate as the blisters grow, resulting in the breakdown of a uranium aluminide particle. These descriptions are based on microscopic examinations over dimensions approaching those of respirable particles. Although the experiments were not conducted under physiological conditions, it is feasible that initially insoluble uranium aluminide particles could undergo the same gradual oxidation and breakdown in the lungs.

The set of respiratory parameter values applied in this study to uranium aluminide is a modification of the ICRP's parameter values for Type S material, i.e., relatively insoluble material with low absorption to blood (Leggett et al. 2005). Parameter values describing retention of Type S material in the alveolar-interstitial region of the lungs were modified to yield low absorption of uranium to blood over the first few months after inhalation. In effect, the modified Type S model depicts uranium aluminide as an initially insoluble material with very low absorption that is gradually transformed in the lungs to a form that is more readily absorbed to blood. The assumed rate of transformation from an insoluble to a moderately soluble material is $0.004\ d^{-1}$, corresponding to a half-time of roughly 0.5 y. With the exception of transformed material in the alveolar-interstitial region, particulate transport is the same as depicted in the ICRP's respiratory model for Type S material.

Gastrointestinal tract model. The model of the gastrointestinal (GI) tract applied in this study is the current GI model of the ICRP (ICRP 1979). The only feature of that model of much importance to the present study is the assumed GI absorption fraction for swallowed activity. The GI absorption fractions or f_1 values for inhaled radionuclides are those currently recommended by the ICRP for workers (ICRP 1994b). The GI absorption fraction for uranium inhaled as aluminide (not addressed by the ICRP) is assumed to be 0.002, the ICRP's value for relatively insoluble forms of U.

Systemic biokinetic models. With three exceptions, the systemic biokinetic models used to interpret bioassay data and calculate organ doses are those currently recommended by the ICRP (ICRP 1993, 1994b, 1995a and b, 1997). The ICRP's current systemic biokinetic models

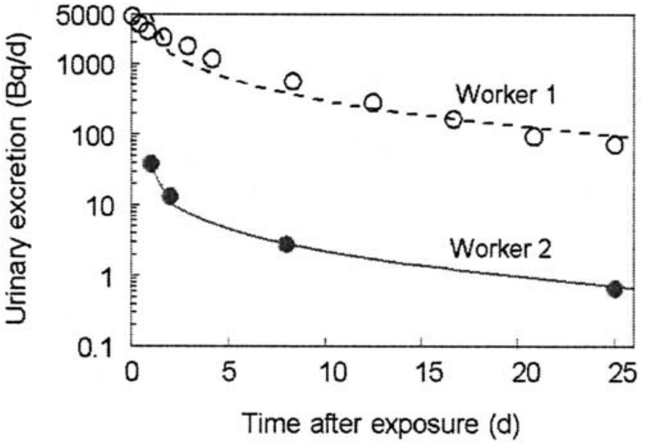


Fig. 4. Model predictions (curves) for acute intake of ^{90}Sr, Type F, AMAD = 5 μm, compared with urinary excretion data for two workers thought to have been acutely exposed to ^{90}Sr and other fission products. Each curve is normalized to the observed excretion rate 1 d after exposure.

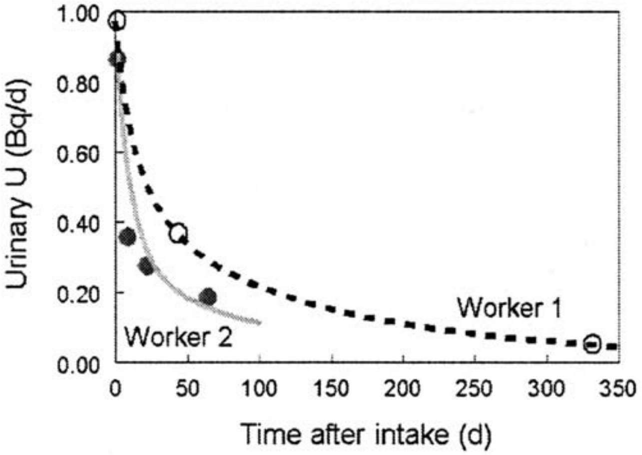


Fig. 5. Model predictions (curves) for acute intake of uranium, Type M, AMAD = 5 μm, compared with urinary excretion data for two workers thought to have been acutely exposed to uranium. Each curve is normalized to the observed excretion rate at 1 d.

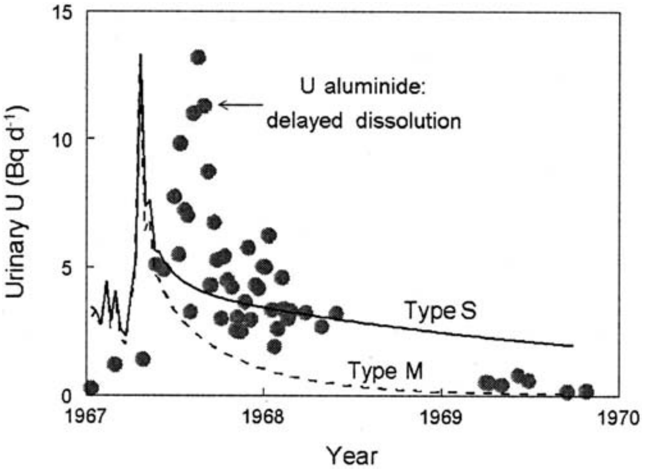


Fig. 6. Urinary excretion data for a worker exposed to uranium aluminide, compared with predictions based on reference absorption types used by the ICRP for moderately soluble (Type M) and relatively insoluble (Type S) material. The intake scenario was based on measured air concentrations during the exposure period.

for polonium, cerium, and promethium were replaced by newer models provisionally adopted by the ICRP for use in an upcoming document on occupational intakes of radionuclides (Leggett and Eckerman 2001; Taylor and Leggett 2003).

Application of models to estimate doses to workers. Estimation of dose from excretion data or in vivo lung counts is done in two steps: a "backward" calculation in which the total intake is estimated on the basis of exposure records and excretion or lung data, and a "forward" calculation in which annual doses are calculated on the basis of the estimated intake. The backward calculation involves determination of an appropriate exposure scenario (that is, a characterization of the material taken into the body and the pattern of exposure over time) and determination of an intake level that provides a good fit between model predictions and excretion and lung data based on the selected exposure scenario, as illustrated in Figs. 4 and 5. In many of the cases addressed in this study, the bioassay data changed in a considerably less regular fashion than indicated in these two figures. In such cases it was more practical, and presumably no less accurate with regard to reconstruction of dose, to fit cumulative excretion of radionuclides rather than attempt to produce a model curve that mimicked the scatter in the data. In such cases the fitting process consisted of integrating urinary excretion data and then identifying a level of intake that gives the same cumulative urinary excretion value over the same period, based on the assigned exposure scenario and biokinetic models.

Assignment of exposure scenarios. Estimates of dose from internally deposited radionuclides may depend strongly on the exposure scenario as well as the biokinetic models applied. Although exposure scenarios were selected on a case-by-case basis and usually depended to some extent on information specific to the exposed worker, most of the cases represented some variation of the general situations summarized below.

In a number of cases, the time of an acute intake of a radionuclide was pinpointed in an incident report, and the behavior of the internally deposited radionuclide over time was revealed by follow-up measurements. Such cases often allowed a check on the appropriateness of the biokinetic models, as illustrated in Figs. 4 and 5.

Other cases of apparently short-term exposure involve only portions of the information described above.

For example, records indicate that a worker apparently inhaled uranium oxide in early to mid-October 1965, but the precise time of exposure is not known. Extensive follow-up measurements are consistent with an elevated intake of uranium around that time.

The time period of chronic exposure to a radionuclide often could be identified generally from collective sources of information such as reports to the Atomic Energy Commission, internal memos, air-monitoring data, bioassay data, and individual work histories. For example, the urinary data in Fig. 6 are for a worker exposed to uranium aluminide from late 1966 to mid-1967, according to reports and memos in his exposure file. Air monitoring data indicating the change with time in the concentration of uranium in air are available for almost all of this period. A reasonable fit to this worker's urinary excretion data based on an exposure scenario built from this information, together with the respiratory model parameters developed for uranium aluminide, is derived from an assumed intake of 100,000 Bq.

Common exposure scenarios were sometimes applied to groups of workers based on simultaneous changes in their bioassay data. For example, a cluster of positive urinary uranium measurements was found for the first few weeks of 1963, with more than 50 workers showing elevated urinary uranium during that period. The patterns of change in the collective data over time suggest that there may have been an incident during the first few days of January 1963. The default assumption for these workers was acute inhalation of moderately soluble uranium (Type M) on 2 January 1963.

As an aid in assigning plausible scenarios to cases with little direct information on the time-course of exposure, a history of known or suspected internal exposures to the Rocketdyne/AI workers was developed in the form of a time line. This exposure time line was based on incident reports and bioassay data extracted from exposure histories of individual workers. Additionally, interviews of former radiation workers were conducted to learn first hand about incidents, exposure circumstances, and work conditions. Approximately 200 potentially important radiation incidents involving a few hundred workers were identified. Nearly all of these cases involved acute releases of radionuclides, but the term "incident" is used broadly here to refer to any situation in which persons were potentially exposed to elevated levels of one or more radionuclides, either acutely or over an extended period.

Default methods applied when exposure patterns were not evident. In numerous cases, intake of radionuclides was indicated by limited, irregular, or widely spaced monitoring data, and no particular exposure pattern was discernable from available information. In such cases, default multipliers were used to estimate intake. These multipliers were selected from distributions of values derived from a variety of plausible exposure scenarios. The multipliers are intended to be robust, i.e., to avoid large overestimates or underestimates in the majority of cases. For example, an isolated urinary uranium measurement of X Bq/d, with no indication of the exposure time, was assumed to represent inhalation of $1600X$ Bq of moderately soluble U (Type M). The multiplier 1,600 was based on consideration of a variety of plausible exposure scenarios, e.g., acute intake at different times in the past six months, or different patterns of chronic intake during that time. Most multipliers derived from these scenarios were in the range 1,000–5,000 and a cluster of estimates fell around 1,600.

Consideration of prior doses. Where feasible, estimates of annual dose from internal exposure include occupational intake of radionuclides prior to employment at Rocketdyne/AI. Fig. 7 shows data for a worker whose estimated internal exposures arose entirely from pre-Rocketdyne/AI employment.

Treatment of less than minimal detectable levels (<MDL). Assignment of a numerical value to a measurement reported as <MDL was determined on a case-by-case basis. The value zero was assigned in the common situation in which no recent exposure was suspected. If exposure was suggested by ancillary information or if the <MDL value was close in time to positive measurements, then the value 0.5 × MDL was usually assigned, but the value MDL was assigned in a few cases where relatively high exposure was suspected. The definition of "close in time" varied somewhat with the material under consideration. For example, it was taken to be a few months for uranium aluminide, for which urinary uranium may remain below the detectable level for an extended period after elevated intake, and a few weeks for moderately soluble uranium (Type M), for which urinary uranium is tied more closely in time to the lung burden.

Relative biological effectiveness of alphas. Radiobiological data indicate that alpha particles and fission neutrons have a larger biological effect than an equal absorbed dose resulting from low-LET radiation. Ranges of estimated values for the relative biological effectiveness (RBE) of high-LET radiations are wide, depending on the observed endpoint, the tissue, and perhaps the animal species. Overall, experimental data for solid tumor induction with alpha particles or fission neutrons suggest a central value of about 10–30 and a range of 6 to 60 for the RBE relative to low-dose, low-LET radiation (NCRP 1990; ICRP 1991; NRC-CEC 1997). The RBE for leukemia appears to be considerably lower than values reported for solid tumor induction (Boice 1993; U.S. EPA 1999). In the present study, an RBE of 20 was applied to absorbed dose from alpha radiation to tissues other than red marrow (ICRP 1991), and an RBE of 1 was applied to absorbed dose to red marrow (Boice 1993; U.S. EPA 1999).

RESULTS

Whole-body doses from external exposures

Whole-body doses from external exposures were obtained in two ways: imaging and abstracting the dosimetry information found within Rocketdyne/AI radiation files and linking the roster of all Rocketdyne workers with various nationwide databases and with facility- or study-specific worker files. Dose distributions are presented in Table 4 for workers monitored and not monitored for radiation at Rocketdyne/AI by period of employment. Overall, 932 (16.1%) of the radiation workforce had prior exposure elsewhere, and 1,224 (21.1%) had subsequent exposure after leaving Rocketdyne. Nearly 32% (or 1,833) of the radiation workers had been employed and monitored for radiation at other facilities. As seen in Fig. 8, including the radiation dose received elsewhere had a noticeable influence on the distribution of doses by increasing the number of workers with relatively high cumulative doses. Based on the Rocketdyne dose only, 231 workers received greater than 50 mSv, but based on all dose information available on external doses, the number who exceeded 50 mSv over their career increased to 331, or by 43%.

The amount of misclassification of worker occupational radiation dose can be seen in Table 5, which presents a cross-tabulation of external dose received only at Rocketdyne/AI by total career dose from all facilities for the 5,743 radiation workers monitored for external radiation at Rocketdyne/AI. The number of workers in the highest category (>200 mSv) increased from 45 to 69 (or 53%), the 100–199 mSv category increased from 58 to 100 (or 72%), whereas the zero dose category decreased from 693 to 601 (or 13%). It can be seen that some workers classified in a relatively low dose category based on their Rocketdyne/AI experience received total career doses that placed them in the highest dose category.

Cumulative organ doses from internal exposures

There were 292 workers whose bioassay measurements or other internal monitoring data indicated that the committed equivalent dose to at least one tissue might exceed 10 mSv, which was the criterion for development of a detailed internal exposure scenario and comprehensive individual organ dose estimates. Organ doses for 16 tissues were estimated for each calendar year after intake up through the year 1999 (Table 6). The "remainder" in Table 6 represents the doses received by all other organs and tissue not explicitly included in the dose computation assessment, and might be considered a soft tissue dose. Cumulative organ doses were computed by summing the annual doses up through 1999 for those alive and to the date of death for those who died. Consistent with the major route of exposure being from inhalation, the lung (mean 106 mSv) and respiratory lymph nodes (mean 300 mSv) had the highest levels. There were 49 workers with cumulative lung doses exceeding 100 mSv (maximum 3,560 mSv). The major contributor to lung dose was uranium aluminide. A small number of workers received cumulative doses exceeding 100 mSv to the bone surface and to the liver. Plutonium and thorium were the main contributors to bone surface dose (maximum 5,890 mSv). Two workers received greater than 50 mSv to the testes and one worker received greater than 10 mSv to the kidney. Other than for the lung, bone surface, liver, and perhaps kidney, the doses to the other organs were small in comparison to the whole-body dose received from external radiation. Overall, most workers monitored for internal radiation (1,940 or 86.9%) had negligible intakes.

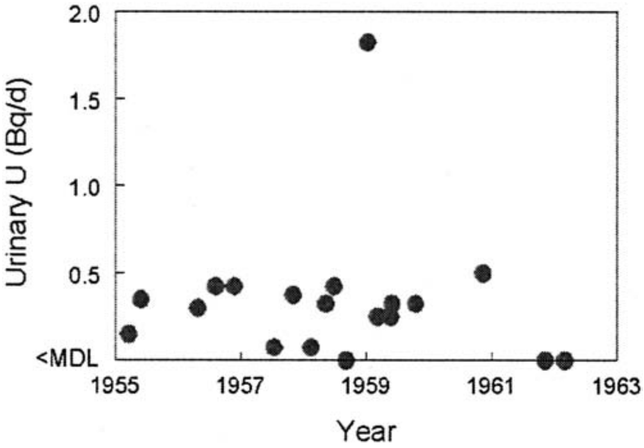


Fig. 7. Urinary data for a worker exposed to uranium before starting work at Rocketdyne/AI in the early 1960's.

Combining external whole-body doses with internal organ doses

As is evident from Table 6, the dose distributions associated with radionuclide intakes for specific organs are substantially different. These differences are due to the wide range of radionuclides (at least 12) contributing to internal doses with their different chemistries and solubility properties. As seen, these different dose distributions are not proportionately related. Accordingly, our epidemiologic analyses used the dose distribution for each specific organ, i.e., the external whole-body dose was added to the internal organ dose for specific cancer site analyses. The internal dose contribution is substantial for the lung and may be important for bone surface, liver, and kidney. For all other organs, few workers received greater than 5 mSv cumulative internal dose and the internal dose contribution was small in comparison with the whole-body external dose received.

Although the number of workers monitored for intakes of radionuclides was 2,232 or 38% of the radiation workforce, it was only the 292 (5.0%) with relatively high internal intakes that contributed to the worker doses as estimated in the present study. For these 292 workers, dose to the lung was of prime importance, and there were few workers with relatively high doses to any other organ. The contribution of internal emitters to lung dose was meaningful (mean 106 mSv, maximum 3,560 mSv) even in comparison with the much larger numbers exposed to external radiation (Fig. 8). Adding the lung dose from internal emitters to that received from external exposures increased the number of Rocketdyne workers who received greater than 50 mSv from 231 (Rocketdyne only) to 427 (or 84.8%). For all sources of external radiation, the number who received greater than 50 mSv increased from 334 to 427 (or 27.8%). Because it was not possible to compute internal doses for radionuclide intakes received at facilities other than at Rocketdyne, other than for a few individuals, it is likely that organ doses will be underestimated in general within this population, but especially for the lung.

Occupational exposure received elsewhere

Table 7 presents the average and range of external and internal radiation doses received at Rocketdyne/AI and at other places of employment. The total collective dose from all sources of penetrating radiation was 78.4 person-Sv, of which 20.8 person-Sv (or 26.5%) was received during employment other than at Rocketdyne.

Fig. 8 provides a visual representation of the influence on cumulative lung dose from exposures experienced at Rocketdyne, at other facilities, and from internal radionuclides. Adding the dose received elsewhere and the internal emitter dose increased the number of high dose exposures (>200 mSv) from 45 to 109, or by a factor of 2.4 (Table 4). The mean dose to the lung for the entire population nearly doubled, increasing from 10.0 mSv to 19.0 mSv (Table 7), as did the person-Sieverts (from 57.4 to 109.4 person-Sv). Just over 5% of workers (*n* = 292) monitored for internal radiation contributed disproportionally (28.3%) to the population lung dose.

Neutrons

Nearly 10% (or 584) of the Rocketdyne/AI radiation workers were monitored for neutron exposures while at Rocketdyne, and another 1.4% (or 81) were monitored for neutron exposures elsewhere. However, only about half (363 or 54%) had positive measurements and there

Table 4. Number of workers monitored and not monitored for radiation at Rocketdyne by cumulative external radiation dose received before, during and after Rocketdyne employment, neutron dose, internal lung dose, and total career dose.[a]

Employment period	Cumulative dose (mSv)							
	0	<5	5-	10-	50-	100-	≥200	Total
Nonradiation workers	639	718	54	49	11	6	0	1,477
Before and after Rocketdyne								
Radiation workers								
External photon radiation dose								
Before Rocketdyne	105	482	97	165	39	30	14	932
While at Rocketdyne	693	3,231	663	925	128	58	45	5,743[b]
After Rocketdyne	744	369	53	41	12	5	0	1,224
TOTAL career, external photons[a]	608	3,155	646	1,009	166	97	68	5,749
Total career, neutron dose	303	314	35	11	2	0	0	665
Total career, external (photon & neutron)	605	3,149	651	1,012	165	100	69	5,751
Internal lung dose	0	24	4	178	37	15	34	292
Total lung dose (all external and internal)[a]	604	3,079	609	1,039	203	113	109	5,756[c]

[a] Note that the columns do not sum to the "total career" dose. This is because when the radiation dose received elsewhere is added to the Rocketdyne dose for individual workers, they can move into a higher dose category. For example, a worker with 7 mSv at Rocketdyne might have received 4 mSv elsewhere and his total career dose of 11 mSv would shift him from the "5-" mSv category into the "10-" mSv category.

[b] 58 workers in the radiation cohort who were monitored only for internal radiation are not included in this total.

[c] 45 workers in the radiation cohort who were monitored only for internal radiation, received no neutron monitoring, and did not have their internal radiation dose modeled (i.e., did not meet 10 mSv internal dose threshold) are not included in this total.

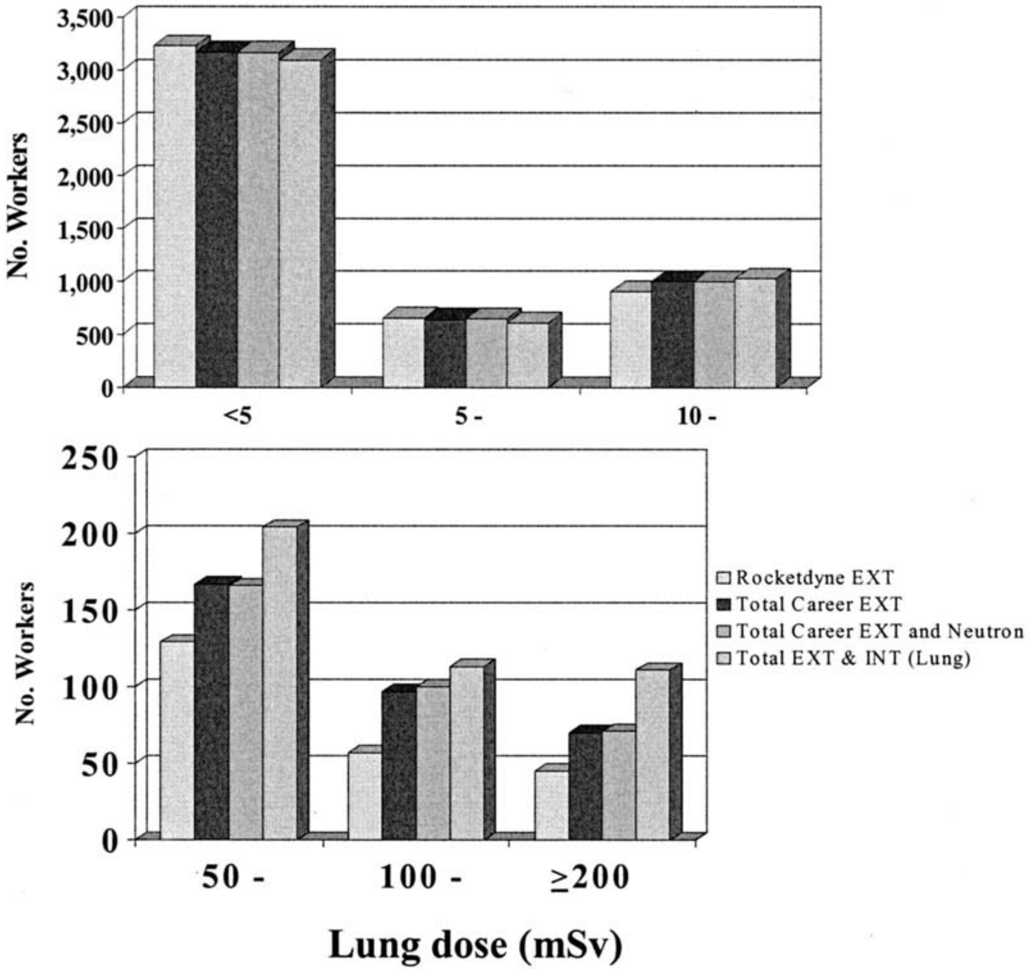


Fig. 8. Distribution of workers by lung dose and source of occupational exposure: external (EXT) photon exposure at Rocketdyne/AI, total career external photon exposure at Rocketdyne/AI and all other facilities, all external (photon and neutron exposure) at Rocketdyne/AI and elsewhere, all external (photon and neutron exposure) and internal (INT) dose from Rocketdyne/AI and all other facilities.

Table 5. Cross-tabulation of external dose received only at Rocketdyne by total career dose from all facilities for the 5,743 radiation workers monitored for external radiation at Rocketdyne.

		External dose (mSv) received during employment at Rocketdyne only							
		0	>0–5	5-	10-	50-	100-	≥200	Total
Total career external dose (mSv)	0	601							601
	>0–5	78	3,067						3,145
	5-	6	78	567					651
	10-	7	61	76	868				1,012
	50-	1	16	7	37	104			165
	100-	0	8	9	14	20	49		100
	200-	0	1	4	6	4	9	45	69
	Total	693	3,231	663	925	128	58	45	5,743

were only 13 workers with cumulative exposures over 10 mSv and none over 100 mSv. In contrast, more than 400 of these same workers had cumulative external exposures of over 10 mSv. Thus the neutron contribution, if validly captured, appears negligible in comparison with the much higher external exposures, contributing less than 3% of the total dose of workers monitored for neutrons and less than 0.1% of the total dose of all radiation workers. In general, there is a concern that neutron doses are underestimated among early radiation workers (Gilbert and Fix 1995), either because there was no monitoring for neutrons, the monitoring devices were not accurate, or the mix of thermal and fast neutrons was unknown and difficult to quantify. It appears that while

Table 6. Cumulative organ doses for 16 tissues from internal exposures for the 292 Rocketdyne workers with the highest radionuclide intake. Dose is estimated for 12 radionuclides up through 1999 for those alive and to the date of death for those who died.

	Cumulative doses (mSv)										
	Dose characteristics			Dose categories							
Organ (radionuclide)[a]	Mean	Median	Range	<1	1-	5-	10-	50-	100-	200-	≥500
Bladder	0.2	0.1	0–9	284	5	3	0	0	0	0	0
Bone surface (^{239}Pu, ^{232}Th, ^{90}Sr)	68.7	3.4	0–5,742	31	150	47	38	11	7	4	4
Brain	0.2	0.1	0–9	284	5	3	0	0	0	0	0
Breast	0.2	0.1	0–9	284	5	3	0	0	0	0	0
Colon	0.3	0.1	0–10	283	6	3	0	0	0	0	0
Esophagus	0.2	0.1	0–9	284	5	3	0	0	0	0	0
Kidney (U Type M + UA1$_x$)	2.6	1.1	0–58	128	136	15	12	1	0	0	0
Liver (^{239}Pu)	14.0	0.5	0–1,246	211	51	6	19	1	0	1	3
Lung (UA1$_x$ + U Type M)	106	24.4	0–3,560	7	17	4	178	37	15	19	15
Respiratory lymph nodes	300	4.1	0–16,736	25	133	31	20	15	17	16	35
Red marrow	0.4	0.0	0–18	279	7	3	3	0	0	0	0
Stomach	0.2	0.1	0–9	284	5	3	0	0	0	0	0
Testes (^{239}Pu)	1.0	0.1	0–78	275	13	0	2	2	0	0	0
Thyroid	0.2	0.1	0–9	284	5	3	0	0	0	0	0
Remainder	0.2	0.1	0–9	284	5	3	0	0	0	0	0

[a] The radionuclide/s typically contributing to the highest organ doses are shown in parentheses.

the number of workers monitored for neutrons is not inconsequential, perhaps 10% of all workers, the measured doses *per se* do not suggest a serious problem for the Rocketdyne/AI workforce.

DISCUSSION

In general, occupational studies of radiation workers must be interpreted carefully because (1) occupational dose received at other nuclear or radiation facilities may be missed; (2) dose from internally deposited radionuclides may be undetermined; (3) dose from neutrons may be unknown; (4) film badge or thermoluminescent dosimeter (TLD) exposures are imperfect measures of organ doses; (5) the dose from natural background radiation (about 170 mSv in 70 years) may be greater than the occupational dose; (6) medical x-ray exposures may be substantial and are rarely available; (7) other occupational and nonoccupational carcinogens (such as tobacco use) are usually not considered; (8) selection biases associated with entry into the work force and continued employment may be likely; and (9) ascertainment bias is possible if the working population receives better medical care and more accurate cancer diagnoses recorded on death certificates than the general population (Greenwald et al. 1981; Gilbert and Fix 1995; UNSCEAR 2000; Daniels et al. 2005; Daniels and Schubauer-Berigan 2005). The current paper addresses directly several of these issues within a comprehensive dosimetry assessment of the Rocketdyne/AI radiation workforce: Does the dose distribution materially change when doses received at other facilities are included? Does the dose distribution materially change when organ doses from internal radionuclides are added? Does the dose distribution materially change when doses from neutrons are taken into account? We were not able to address directly several issues of potential importance, such as natural background radiation or exposure to technically enhanced radioactive materials or medical x rays, because of the absence of available exposure documents.

Table 7. Average and range of external penetrating dose (photons and neutrons) and internal lung dose (mSv) for workers monitored for radiation at Rocketdyne by period of employment.

Period of employment	*N*	Mean (mSv)	Maximum (mSv)	Person-Sv
Before Rocketdyne, photons	932	19.0	999	17.7
While at Rocketdyne, photons	5,743	10.0	500	57.4
After Rocketdyne, photons	1,224	2.5	159	3.1
Total career, all periods, photons	5,749	13.5	1,005	77.6
Total career, all periods, neutrons	665	1.2	56	0.8
Internal lung dose	292	106.2	3,560	31.0
Total lung dose, all external and internal	5,756	19.0	3,577	109.4

Major conclusions are that doses received at other facilities are important and meaningfully increase the number of workers with relatively high career doses; that a small number of workers exposed to internal radionuclides can significantly alter the shape of the dose distribution for certain organs; and that neutron exposures apparently were low and had little influence on the shape of the dose distributions. Other findings of note are that nearly 4% of non-radiation workers were monitored for radiation elsewhere during their careers; existing biokinetic models for radionuclides are not always sufficient to compute organ doses for uncommon radioactive compounds; and that exhaustive attempts to collect lifetime career doses for radiation workers may still underestimate exposures because of the difficulty in capturing all occupational doses, e.g., doses for workers employed by the U.S. Navy were not available except for a few workers, and because of the difficulty in determining, much less computing, organ doses, for radionuclide intakes and neutron exposures received elsewhere.

As mentioned above, this paper does not address all the possible uncertainties in dose reconstruction but focuses on the three that potentially could result in spurious epidemiologic conclusions, i.e., occupational doses received elsewhere, inadequate handling of organ doses from internal radionuclide intakes, and ignoring neutron exposures. Other assumptions commonly made in epidemiologic investigations of radiation workers deal with low dose recording conventions, missing data, exposure geometry, dosimetry system, and type of recorded data. There were few external dosimeter data values that were recorded as "less than some small number," and these and "zeros" were treated as if no dose were received during the reporting period, usually every 3 mo. Because we had seven overlapping sources of external radiation, the likelihood of missing a significant amount of dosimetry reports appears small. For external doses, no geometric adjustments were made (i.e., whether the exposure was AP, PA, lateral or isotropic), and we assumed that the measured dose was a good approximation of the organ dose as is done in practically all occupational studies of radiation workers. The methods of measuring external dose changed over the years, from film badge to TLD to OSL (optically stimulated luminescence), and exposures were reported in a variety of endpoints (such as shallow dose, penetrating dose, beta dose, photon dose, neutron dose). For the doses used in the epidemiologic investigation, we did not assume that the measured dose differed by type of dosimetry system used, and in all cases penetrating dose was used as the best estimate for organ dose. The other reported doses were not used, except the neutron dose when recorded.

The radiation dosimetry approach taken in the current study differs from the one used in the previous study, making direct comparisons problematic (Ritz et al. 1999, 2000; Morgenstern and Ritz 2001). Differences include the selection criteria for cohort members; the efforts made to capture and incorporate radiation doses received elsewhere, the inclusion of neutron doses, and the estimation of dose following the intake of radionuclides. Our study population is larger by about 1,200 radiation workers than the previous study for reasons that are not entirely clear since essentially the same Rocketdyne files formed the basis of the study cohorts. There were differences in selection criteria in that we included workers employed between 1948–1999 but excluded those who worked less than 6 mo, whereas the previous study included all workers monitored for radiation between 1950–1993, and made no exclusions based on duration of employment. Most of the differences, however, appeared in our including more workers with low doses of <5 mSv. We also made an intensive effort to obtain additional radiation doses received at installations other than at Rocketdyne and incorporated these doses in the epidemiologic analyses. The previous study recorded, but did not use, the prior employment doses for over 400 workers from available notices in the Rocketdyne radiation folders, whereas we found 932 workers with prior doses from the record linkage approaches described as well as an additional 1,224 instances of workers who were monitored for radiation after leaving Rocketdyne/Atomics International. Nearly 10% of the radiation cohort was monitored for neutron exposures at Rocketdyne and another 2% were monitored for neutron exposures elsewhere. We incorporated these neutron doses in each worker's total career dose, whereas they were excluded in the previous study. The last important difference is in the approach to internal dosimetry. We used the latest ICRP biokinetic models for organ dose determinations for 12 radionuclides, including three models provisionally adopted for upcoming ICRP reports and one model that we independently developed for uranium aluminide (Leggett et al. 2005). We computed doses for 16 different organs or tissues up until the time of death or to the end of study in 1999. The previous study considered only about 5 radionuclides, used outdated ICRP biokinetic models, and only calculated cumulative equivalent doses to the lung and no other organ. The estimated lung doses were used in the previous study to approximate the doses to all other organs and tissues, but this does not appear from our more detailed estimates to be a valid assumption (Table 6).

The computation of organ doses following intake of radionuclides for use in an epidemiologic study differs from the normal procedures used in radiation protection.

An epidemiologic investigation requires a radiation dose to a specific organ that is received up to some period of time prior to the diagnosis of a malignancy or an equivalent time for those without disease. For radiation protection, the committed effective dose is computed following an intake that projects the effective dose over a period of 50 y based on administratively defined tissue and radiation weighting factors (ICRP 1991). In this study, a major effort was made to compute annual organ doses from inhaled or ingested radionuclides for 16 specific organs or tissues, and the ICRP models were modified accordingly. Effective dose is not appropriate for epidemiologic analyses and was not computed (Cox and Kellerer 2003).

The computation of organ doses following intake of radionuclides for use in an epidemiologic study is in principle the same as the computation performed for an individual for compensable considerations, although the completeness of the bioassay and dosimetry data available for Rocketdyne/AI workers is rather exceptional and there was little uncertainty in the fact of exposure or the relative intake. Nonetheless, we did not perform the laborious dose reconstruction computations when the organ doses were clearly inconsequential, i.e., for workers with committed equivalent doses indicated by screening criteria to be less than 10 mSv to the organ with the highest internal dose. Similar considerations might be made for radiation workers or atomic veterans when the available dosimetry is sparse or missing (Office of Workers' Compensation 2005; NRC 2003, 2005). For individuals with missing dosimetry but whose exposure group is reasonably well known, the maximum known intake for the individuals in the exposure group could be assigned to those individuals with uncertain exposure. If based on this "maximum assumption" the computed organ doses are substantially less than what would be required for compensation, then a dose reconstruction would not be necessary. If the maximum dose results in a probability of causation (assigned share) value that was above a compensable level, then the individuals in the group could receive compensation based on the legal mandate to err on the side of compassion and for the benefit of the exposed individual.

Those employed in the early years of the atomic age often worked at several facilities during their career making it difficult to collect dose information received elsewhere, especially from subsequent places of employment, which are rarely recorded in worker files. Exposures to inhaled or ingested radionuclides are difficult to quantify in terms of organ doses even when complete bioassay measurements and sophisticated biokinetic models are available. Neutron exposures were often not recorded or were poorly estimated. Workers prior to about 1970 could have received occupational x-ray examinations, including photofluorography, which could be large and might even be considered part of their occupational exposure (Daniels et al. 2005). The consequences of these limitations and uncertainties could lead to a serious underestimation of dose for workers and an overestimation of the risk at low doses, or perhaps to such serious misclassification that results might not be interpretable. Until recently, few ways were available to address these problems, although sensitivity analyses have been conducted to estimate the magnitude of possible biases (Gilbert and Fix 1995).

Over the years, a wide range of approaches have been taken by various investigators to deal with transfer doses, i.e., doses received at facilities other than the one being studied, neutron exposures, and doses from internally deposited radionuclides. Transfer doses received prior to employment at the study facility have been included in some studies when known (Gilbert et al. 1993a and b; McGeoghegan and Binks 2000a and b, 2001; McGeoghegan et al. 2003), excluded in some studies when known (Ritz et al. 1999; Wing et al. 2004), but are usually not considered except perhaps in nationwide dose registry studies where it is assumed that most, but not all, radiation installations have contributed to the database (Muirhead et al. 1999; Sont et al. 2001; Iwasaki et al. 2003). Few investigations have been able to determine radiation exposures for workers who have left a particular facility. More than half (500/932) of the Rocketdyne/AI workers found to have been monitored for radiation prior to joining Rocketdyne had no mention of this previous radiation experience in their folders, and, not surprisingly, practically all of the subsequent exposures received elsewhere by over 21% (1,224/5,801) of the workforce were not mentioned.

Except for large-scale epidemiologic studies of plutonium workers in the United Kingdom and in Russia, few if any epidemiologic studies have attempted to compute organ doses following the ingestion or inhalation of radionuclides. Although internal radiation was not considered in the early analyses of Sellafield workers (Douglas et al. 1994), recent comprehensive reports have incorporated organ-specific doses from plutonium (Riddell et al. 2000; Riddell 2002), and some analyses were based on the total dose from external exposure and internal emitters (Omar et al. 1999). Individual assessments had been made for perhaps 20% of the workforce because of special circumstances such as statutory requirements, compensation, and operational protection. For the remaining workers, an automated assessment program was used to characterize doses based on available urinalysis results and other factors. Some studies have considered the fact that workers were monitored (or had the potential to be monitored) for radionuclides in the analyses (Frome et al. 1997; Beral et al. 1988; Fraser et al. 1993; Carpenter et al. 1998), others were aware of radionuclide exposures but apparently did not sort them out of the analyses (Wiggs et al. 1991; Inskip et al. 1987; Carpenter et al. 1994; Rooney et al. 1993; Cardis et al. 1995; Muirhead et al. 1999; Dupree-Ellis et al. 2000; McGeoghegan and Binks 2000a and b), and others excluded workers monitored for internal radionuclides (Gilbert et al. 1993a, and b; Cardis et al. 2005).

Comprehensive dosimetry continues for Mayak workers in Russia exposed to very high levels of plutonium, i.e., body burdens of the order of 4–6 kBq, and organ doses have been computed for lung, liver and bone surfaces and other organs. Both body burdens and organ doses from plutonium and external doses have been analyzed in a variety of ways (Koshurnikova et al. 1998, 2000; Gilbert et al. 2000; IARC 2001; Kreisheimer et al. 2003; Shilnikova et al. 2003). In the United States, dose-response analyses have been conducted of internal intakes of plutonium, but body burdens and not organ doses were used (Wiggs et al. 1994; Wilkinson et al. 1987; Voelz et al. 1997). In contrast to the Mayak studies, the body burdens were quite low in the U.S. worker studies, most on the order of 100 Bq, or about 50 times lower than those in Russian workers. The previous study of Rocketdyne workers computed lung dose equivalents for five radionuclides based on bioassay measurements (Ritz et al. 1999). One study of Hanford plutonium workers based analyses on job titles alone and not on available bioassay data (Wing et al. 2004). A recent study of Rocky Flats plutonium workers estimated annual equivalent lung doses based on urinary bioassay data and lung counts using the computer code CINDY (Brown et al. 2004).

In our conduct of the dose compilations, we were able to address several important issues regarding the estimation of internal exposure for epidemiological settings. In an epidemiological scheme relying on organ dose as an analogue for risk, we demonstrated that body burdens do not provide a consistent indicator of such risk. Since the chemical properties of the radioactive material determines its retention in the body and additionally influences the nuclide's behavior in specific organs of concentration, and since organ dose is directly dependent upon these physiological processes (e.g., Priest 1989), the only valid way to estimate dose to an organ was through modeling. We found that for the Rocketdyne workers, the computed body burden would result in widely divergent doses between organs, i.e., the lung generally received doses significantly higher than other evaluated organ sites and, coupled with the different types of radionuclides contributing to organ doses, there was no proportional relationship between dose to lung and dose to other organs as assumed in the previous study (Ritz et al. 2000). Thus, an implicit assumption that a body burden imparted a universal or linear risk to all organs of the body was demonstrated to be unsupportable. We also found that most persons monitored for radionuclides did not have positive readings, thus making categorization by job title or other work activity-based schemes unreliable.

Neutron exposures have been inconsistently handled also. Some studies recorded and analyzed neutron doses (Inskip et al. 1987), others excluded neutron-exposed workers in some analyses (Cardis et al. 1995, 2005), and others ignored the neutron dose (Ritz et al. 1999). Other studies noted neutron exposures but did not address them in the analyses (Gilbert et al. 2000, 1993b). Although nearly 12% of the Rocketdyne workforce was monitored for neutron exposures, the contribution to total dose was not great. It is generally agreed, however, that neutron exposures were poorly estimated in the early years of the atomic age (Gilbert 1993b).

The problem associated with excluding workers for whatever reason can be a reduction in study power, which might be further exacerbated if excluded workers are those likely to have received relatively high exposures. Validity could be affected, however, if workers with radionuclide intakes, neutron exposures, and doses received at other facilities are inappropriately handled. We attempted to address these uncertainties by seeking exposure histories from all sources available, computing organ-specific annual doses following internal radionuclide intakes, and recording and incorporating all available neutron exposure data.

In conclusion, while the Rocketdyne/AI radiation study is limited because of the relatively small number of workers and narrow range of organ doses, it nonetheless illustrates some of the pitfalls in conducting occupational studies of low doses where seemingly minor uncertainties can have a substantial impact on the estimation of population doses. Exposures received elsewhere increased the collective dose by 38% and the contribution of radionuclide intakes to certain organs greatly increased the number of workers with high doses; e.g., the lung dose person-Sv was increased by 55%. While the number of workers monitored for neutron exposures was not small, the actual neutron dose recorded did not appreciably affect the dose distributions. A small percentage (3.6%) of non-radiation workers were also found to have been monitored for radiation elsewhere. These sources of bias should be considered when interpreting results from radiation studies of workers.

Acknowledgments—We thank the U.S. Department of Energy (Nimi Rao), the Nuclear Regulatory Commission (Rosemary Hogan and Sheryl Burrows), SAIC (Derek A. Hagemeyer), the U.S. Army Radiation Standards and Dosimetry Laboratory (William S. Harris, Jr., CHP) and the U.S. Air Force Radiation Surveillance Division, Air Force Institute for Operational Health (Gerald Achenbach and Mike Klueber) for providing linkages with their respective dosimetry files. We are grateful for the helpful advice provided by Barbara Brooks (CEDR Program Coordinator, DOE), James G. Barnes, CHP (Radiation Safety Officer, Rocketdyne, The Boeing Company), and Judy McLaughlin (Rocketdyne, The Boeing Company). The study was supported in part by a competitive contract from The Boeing Company and was conducted with cooperation from the United Automobile, Aerospace and Agricultural Implement Workers of America (UAW) and from Oak Ridge Institute for Science and Education (ORISE) through an interagency agreement with the U.S. DOE. ORISE is managed by Oak Ridge Associated Universities under DOE contract number DE-AC05-00OR22750. The results presented herein represent the conclusions and opinions solely of the authors. Its publication does not imply endorsement by The Boeing Company, the UAW, or any of the acknowledged agencies.

REFERENCES

Beral V, Fraser P, Carpenter L, Booth M, Brown A, Rose G. Mortality of employees of the Atomic Weapons Establishment, 1951–82. Br Med J 297:757–770; 1988.

Bland RD. A parametric study of ion-plated aluminum coatings on uranium. Electrochem Tech 6:272–278; 1968.

Boice JD Jr. Leukemia risk in thorotrast patients. Radiat Res 134:224–233; 1993.

Boice JD Jr. Ionizing radiation. In: Schottenfeld D, Fraumeni JF, Jr, eds. Cancer epidemiology and prevention. New York: Oxford University Press; 2006: 256–293.

Brown SC, Schonbeck MF, McClure D, Baron AE, Navidi WC, Byers T, Ruttenber AJ. Lung cancer and internal lung doses among plutonium workers at the Rocky Flats Plant: a case-control study. Am J Epidemiol 160:163–172; 2004.

Buddery JH, Clark ME, Pearce RJ, Stobbs JJ. The development and properties of an oxidation-resistant coating for uranium. J Nucl Mat 13:169–181; 1964.

Cardis E, Gilbert ES, Carpenter L, Howe G, Kato I, Armstrong BK, Beral V, Cowper G, Douglas A, Fix J, Kaldor J, Lave C, Salmon L, Smith PG, Voelz GL, Wiggs LD. Effects of low doses and low dose rates of external ionizing radiation: cancer mortality among nuclear industry workers in three countries. Radiat Res 142:117–132; 1995.

Cardis E, Vrijheid M, Blettner M, Gilbert E, Hakama M, Hill C, Howe G, Kaldor J, Muirhead CR, Schubauer-Berigan M, Yoshimura T, Bermann F, Cowper G, Fix J, Hacker C, Heinmiller B, Marshall M, Thierry-Chef I, Utterback D, Ahn Y-O, Amoros E, Ashmore P, Auvinen A, Bae J-M, Bernar Solano J, Biau A, Combalot E, Deboodt P, Diez Sacristan A, Eklof M, Engels H, Engholm G, Gulis G, Habib R, Holan K, Hyvonen H, Kerekes A, Kurtinaitis J, Malker H, Martuzzi M, Mastauskas A, Monnet A, Moser M, Pearce MS, Richardson DB, Rodriguez-Artalejo F, Rogel A, Tardy H, Telle-Lamberton M, Turai I, Usel M, Veress K. Risk of cancer after low doses of ionising radiation: Retrospective cohort study in 15 countries. BMJ 331:77; 2005.

Carpenter L, Higgins CD, Douglas A, Fraser P, Beral V, Smith P. Combined analysis of mortality in three United Kingdom nuclear industry workforces, 1946–1988. Radiat Res 138:224–238; 1994.

Carpenter LM, Higgins, Douglas AJ, Maconochie NES, Omar RZ, Fraser P, Beral V, Smith PG. Cancer mortality in relation to monitoring for radionuclide exposure in three UK nuclear industry workforces. Br J Cancer 78:1224–1232; 1998.

Cox R, Kellerer AM. A current view in radiation weighting factors and effective dose. Oxford: Pergamon Press; ICRP Pub 92; Ann ICRP 33:1–4; 2003.

Daniels RD, Schubauer-Berigan MK. Bias and uncertainty of penetrating photon dose measured by film dosemeters in an epidemiological study of US nuclear workers. Radiat Protect Dosim 113:275–289; 2005.

Daniels RD, Kubale TL, Spitz HB. Radiation exposure from work-related medical x-rays at the Portsmouth Naval Shipyard. Am J Ind Med 47:206–216; 2005.

Douglas AJ, Omar RZ, Smith PG. Cancer mortality and morbidity among workers at the Sellafield plant of British Nuclear Fuels. Br J Cancer 70:1232–1243; 1994.

Dupree-Ellis E, Watkins J, Ingle JN, Phillips J. External radiation exposure and mortality in a cohort of uranium processing workers. Am J Epidemiol 152:91–95; 2000.

Fraser P, Carpenter L, Maconochie N, Higgins C, Booth M, Beral V. Cancer mortality and morbidity in employees of the United Kingdom Atomic Energy Authority, 1946–86. Br J Cancer 67:615–624; 1993.

Frome EL, Cragle DL, Watkins JP, Wing S, Shy CM, Tankersley WG, West CM. A mortality study of employees of the nuclear industry in Oak Ridge, Tennessee. Radiat Res 148:64–80; 1997.

Fry SA, Dupree EA, Sipe AH, Seiler DL, Wallace PW. A study of mortality and morbidity among persons occupationally exposed to >50 mSv in a year: phase I, mortality through 1984. Appl Occup Environ Hyg 11:334–343; 1996.

Gilbert ES. Accounting for errors in dose estimates used in studies of workers exposed to external radiation. Health Phys 74:22–29; 1998.

Gilbert ES. Invited commentary: studies of workers exposed to low doses of radiation. Am J Epidemiol 153:319–322; discussion 323–324; 2001.

Gilbert ES, Fix JJ. Accounting for bias in dose estimates in analyses of data from nuclear worker mortality studies. Health Phys 68:650–660; 1995.

Gilbert ES, Omohundro E, Buchanan JA, Holter NA. Mortality of workers at the Hanford site: 1945–1986. Health Phys 64:577–590; 1993a.

Gilbert ES, Cragle DL, Wiggs LD. Updated analyses of combined mortality data for workers at the Hanford Site, Oak Ridge National Laboratory, and Rocky Flats Weapons Plant. Radiat Res 136:408–421; 1993b.

Gilbert ES, Fix JJ, Baumgartner WV. An approach to evaluating bias and uncertainty in estimates of external dose obtained from personal dosimeters. Health Phys 70:336–345; 1996.

Gilbert ES, Koshurnikova NA, Sokolnikov M, Khokhryakov VF, Miller S, Preston DL, Romanov SA, Shilnikova NS, Suslova KG, Vostrotin VV. Liver cancers in Mayak workers. Radiat Res 154:246–252; 2000.

Giles RD, Tavender LE. Preparation and properties of UAlx coatings formed on uranium via the electrophoretic deposition of aluminium powder. J Nucl Mat 24:129–140; 1967.

Greenwald P, Friedlander BR, Lawrence CE, Hearne T, Earle K. Diagnostic sensitivity bias—an epidemiologic explanation for an apparent brain tumor excess. J Occup Med 23:690–694; 1981.

Inskip H, Beral V, Fraser P, Booth M, Coleman D, Brown A. Further assessment of the effects of occupational radiation exposure in the United Kingdom Atomic Energy Authority mortality study. Br J Ind Med 44:149–160; 1987.

International Agency for Research on Cancer. IARC monographs on the evaluation of carcinogenic risks to humans.

Vol 78. Ionizing radiation, part 2: Some internally deposited radionuclides. Lyon, France: IARC; 2001.

International Commission on Radiological Protection. Limits for intakes of radionuclides by workers. Part 1. Oxford: Pergamon Press; ICRP Publication 30; Ann. ICRP, Vol. 2, No. 3/4; 1979.

International Commission on Radiological Protection. 1990 recommendations of the International Commission on Radiological Protection. Oxford: Pergamon Press; Publication 60; Ann. ICRP, Vol. 21; 1991.

International Commission on Radiological Protection. Age dependent doses to members of the public from intake of radionuclides. Part 2. Oxford: Pergamon Press; ICRP Publication 67; 1993.

International Commission on Radiological Protection. Dose coefficients for intakes of radionuclides by workers: replacement of ICRP Publication 61. Oxford: Pergamon Press; ICRP Publication 68; Ann. ICRP, Vol. 24; 1994a.

International Commission on Radiological Protection. Human respiratory tract model for radiological protection. Oxford: Pergamon Press; ICRP Publication 66; Ann. ICRP, Vol. 26, No. 1; 1994b.

International Commission on Radiological Protection. Age-dependent doses to members of the public from intake of radionuclides. Part 3. Ingestion dose coefficients. Oxford: Pergamon Press; ICRP Publication 69; Ann. ICRP 25, No 1; 1995a.

International Commission on Radiological Protection. Age-dependent doses to members of the public from intake of radionuclides. Part 4. Inhalation dose coefficients. Oxford: Pergamon Press; ICRP Publication 71; Ann. ICRP 25, No. 3–4; 1995b.

International Commission on Radiological Protection. Individual monitoring for internal exposure of workers. Oxford: Pergamon Press; ICRP Publication 78; 1997.

Iwasaki T, Murata M, Ohshima S, Miyake T, Kudo S, Inoue Y, Narita M, Yoshimura T, Akiba S, Tango T, Yoshimoto Y, Shimizu Y, Sobue T, Kusumi S, Yamagishi C, Matsudaira H. Second analysis of mortality of nuclear industry workers in Japan, 1986–1997. Radiat Res 159:228–238; 2003.

Koshurnikova NA, Bolotnikova MG, Ilyin LA, Keirim-Markus IB, Menshikh ZS, Okatenko PV, Romanov SA, Tsvetkov VI, Shilnikova NS. Lung cancer risk due to exposure to incorporated plutonium. Radiat Res 149:366–371; 1998.

Koshurnikova NA, Gilbert ES, Sokolnikov M, Khokhryakov VF, Miller S, Preston DL, Romanov SA, Shilnikova NS, Suslova KG, Vostrotin VV. Bone cancers in Mayak workers. Radiat Res 154:237–245; 2000.

Kreisheimer M, Sokolnikov ME, Koshurnikova NA, Khokhryakov VF, Romanow SA, Shilnikova NS, Okatenko PV, Nekolla EA, Kellerer AM. Lung cancer mortality among nuclear workers of the Mayak facilities in the former Soviet Union. An updated analysis considering smoking as the main confounding factor. Radiat Environ Biophys 42:129–135; 2003.

Le Claire AD, Bear IJ. The interdiffusion of uranium and aluminum. J Nucl Energy 2:229–242; 1956.

Leggett RW, Eckerman KF. A systemic biokinetic model for polonium. Sci Total Environ 275:109–125; 2001.

Leggett RW, Eckerman KF, Boice JD, Jr. A respiratory model for uranium aluminide based on occupational data. J Radiol Prot 25:405–416; 2005.

McGeoghegan D, Binks K. The mortality and cancer morbidity experience of workers at the Capenhurst uranium enrichment facility 1946–95. J Radiol Prot 20:381–401; 2000a.

McGeoghegan D, Binks K. The mortality and cancer morbidity experience of workers at the Springfields uranium production facility, 1946–95. J Radiol Protect 20:111–137; 2000b.

McGeoghegan D, Binks K. The mortality and cancer morbidity experience of employees at the Chapelcross plant of British Nuclear Fuels plc, 1955–95. J Radiol Prot 21:221–250; 2001.

McGeoghegan D, Gillies M, Riddell AE, Binks K. Mortality and cancer morbidity experience of female workers at the British Nuclear Fuels Sellafield plant, 1946–1998. Am J Ind Med 44:653–663; 2003.

Morgenstern H, Ritz B. Effects of radiaiton and chemical exposures on cancer mortality among Rocketdyne workers: a review of three cohort studies. Occup Med 16:219–237; 2001.

Muirhead CR, Boice JD, Jr, Raddatz CT, Yoder RC. Comparison of dose histories for U.S. nuclear power plant workers, based on records held by a major dosimetry service company and on the NRC REIRS database. Health Phys 70:645–650; 1996.

Muirhead CR, Goodill AA, Haylock RG, Vokes J, Little MP, Jackson DA, O'Hagan JA, Thomas JM, Kendall GM, Silk TJ, Bingham D, Berridge GL. Occupational radiation exposure and mortality: second analysis of the National Registry for Radiation Workers. J Radiol Prot 19:3–26; 1999.

National Council on Radiation Protection and Measurements. The relative biological effectiveness of radiations of different quality. Bethesda, MD: National Council on Radiation Protection and Measurements; NCRP Report No. 104; 1990.

National Research Council. Committee to Review the Dose Reconstruction Program of the Defense Threat Reduction Agency. A review of the dose reconstruction program of the Defense Threat Reduction Agency. Washington, DC: National Academy Press; 2003.

National Research Council. Assessment of the scientific information for the Radiation Exposure Screening and Education Program. Washington DC: National Academies Press; 2005.

Nuclear Regulatory Commission and the Commission of European Communities. Probabilistic accident consequence uncertainty analysis. Late health effects uncertainty assessment. Washington, DC: U.S. Nuclear Regulatory Commission; Luxembourg: Office for Publications of the European Communities; NUREG/CR-6555; EUR 16774; SAND97-2322; 1997.

Office of Workers' Compensation Programs, Employment Standards Administration, Labor. Performance of functions; claims for compensation under the Energy Employees Occupational Illness Compensation Program Act. Interim final rule; request for comments. Fed Regist 70:33589–33639; 2005.

Omar RZ, Barber JA, Smith PG. Cancer mortality and morbidity among plutonium workers at the Sellafield plant of British Nuclear Fuels. Br J Cancer 79:1288–1301; 1999.

Priest ND. Alpha-emitters in the skeleton: an evaluation of the risk of leukaemia following intakes of plutonium 239. In: Taylor DM, Mays CW, Gerber GB, Thomas RG, eds. Risks from radium and thorotrast. Report 21. London: British Institute of Radiology; 1989: 159–165.

Riddell AE. Advances in the assessment of internal dose for workforce epidemiological studies. In: Proceedings of Fourth International Conference on Health Effects of Low Radiation. Paper 9. Oxford: British Nuclear Energy Society; 2002.

Riddell AE, Battersby WP, Peace MS, Strong R. The assessment of organ doses from plutonium for an epidemiological study of the Sellafield workforce. J Radiol Prot 20:275–286; 2000.

Ritz B, Morgenstern H, Froines J, Young BB. Effects of exposure to external ionizing radiation on cancer mortality in nuclear workers monitored for radiation at Rocketdyne/Atomics International. Am J Ind Med 35:21–31; 1999.

Ritz B, Morgenstern H, Crawford-Brown D, Young B. The effects of internal radiation exposure on cancer mortality in nuclear workers at Rocketdyne/Atomics International. Environ Health Perspect 108:743–751; 2000.

Rooney C, Beral V, Maconochie N, Fraser P, Davies G. Case-control study of prostatic cancer in employees of the United Kingdom Atomic Energy Authority. BMJ 307:1391–1397; 1993.

Shilnikova NS, Preston DL, Ron E, Gilbert ES, Vassilenko EK, Romanov SA, Kuznetsova IS, Sokolnikov ME, Okatenko PV, Kreslov VV, Koshurnikova NA. Cancer mortality risk among workers at the Mayak nuclear complex. Radiat Res 159:787–798; 2003.

Sont WN, Zielinski JM, Ashmore JP, Jiang H, Krewski D, Fair ME, Band PR, Letourneau EG. First analysis of cancer incidence and occupational radiation exposure based on the National Dose Registry of Canada. Am J Epidemiol 153:309–318; 2001.

Subramanyam D, Notis MR, Goldstein JI. Microstructural investigation of intermediate phase formation on uranium-aluminum diffusion couples. Metallurgical Transactions 16A:589–595; 1985.

Taylor DM, Leggett RW. A generic biokinetic model for predicting the behaviour of the lanthanide elements in the human body. Radiat Prot Dosim 105:193–198; 2003.

United Nations Scientific Committee on the Effects of Atomic Radiation. UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes. Sources and effects of ionizing radiation. New York: United Nations; E.00.IX.4; 2000.

U.S. Environmental Protection Agency. Cancer risk coefficients for environmental exposure to radionuclides. Washington, DC: Environmental Protection Agency; Federal Guidance Report No. 13, EPA402R99001; 1999.

Voelz GL, Lawrence JNP, Johnson ER. Fifty years of plutonium exposure to the Manhattan Project plutonium workers: an update. Health Phys 73:611–619; 1997.

Wiggs LD, Cox-Devore CA, Voelz GL. Mortality among a cohort of workers monitored for Po-210 exposure: 1944–1972. Health Phys 61:71–76; 1991.

Wiggs LD, Johnson ER, Cox-DeVore CA, Voelz GL. Mortality through 1990 among white male workers at the Los Alamos National Laboratory: considering exposures to plutonium and external ionizing radiation. Health Phys 67:577–588; 1994.

Wilkinson GS, Tietjen GL, Wiggs LD, Galke WA, Acquavella JF, Reyes M, Voelz GL, Waxweiler RJ. Mortality among plutonium and other radiation workers at a plutonium weapons facility. Am J Epidemiol 125:231–250; 1987.

Wing S, Richardson D, Wolf S, Mihlan G. Plutonium-related work and cause-specific mortality at the United States Department of Energy Hanford Site. Am J Ind Med 45:153–164; 2004.

■ ■