

**Table 1.** Short review of studies assessing occupational exposure among nuclear workers by using job-exposure matrix approach

Reference	Industry	Exposure	Exposure estimator	Exposure assessment method	Purpose, study design and main results	Reviewer's comments
Eheman et al., 1999	All involving radiation	External radiation dose	Discrete annual dose distribution with 6 dose categories, Distribution of cumulative dose, geometric mean and standard deviation	Published dosimetry data for different occupational groups	To estimate radiation doses and uncertainty for individuals reported	Use of radioprotection dosimetry data. No assessment of internal radiation exposure
Germany	exposure			Interview for job history		
	1960-80			Monte Carlo method	occupational radiation exposure in	
					Population based Case-Control study of Non-Hodgkin's lymphoma	
Krishnadasan et al., 2007	Rocket engine and nuclear	TCE, benzene, hydrazine, PHA, mineral oils	Exposure score for each chemical=intensity of exposure (4-level scale) by exposure (4-level scale) by 3 time periods x duration of employment	Coding of likelihood and intensity of exposure by job title by hygienist based on knowledge from facility records and workers survey and interviews	To assess a relationship between occupational exposure to chemicals in the Nested Case-Control study of prostate cancer incidence	Available data on life style habits and familial history of prostate cancer, occupational physical activity intensity.
USA	power testing facility					
	1950-90				Dose-response relationship with TCE	Study with etiological issue

		exposure				
Krishnadasan et al., 2008	Rocket engine and nuclear power testing facility	Occupational physical activity	Score of occupational physical activity based on intensity (3-level scale) of occupational physical activity for a job held longest x duration of employment	Coding of intensity of physical activity by job title by hygienist based on knowledge from facility records and workers survey and interviews	To assess a relationship between occupational physical activity in the Nested Case-Control study of prostate cancer incidence	Data on life style habits and familial history of prostate cancer, available for a limited number of subjects. Job titles used as an entry to JEM despite discrepancies in physical activity level results among radiation and aerospace workers.
USA						
Boice et al., 2006	Rocket engine testing facility	TCE and hydrazine. Other chemicals as surrogate for exposure to all other chemicals	Potential of exposure (no, possible and likely exposure) and cumulative potential exposure for hydrazine and TCE. Duration of employment as a test stand mechanic	Review of worker's exposure history, year, place, and type of work. Validation based on walkthrough visits, interviews with workers, review of workers' medical records	To assess mortality among rocket engines testing workers. Nonsignificant relationship between TCE and kidney cancer. No relationship between test	Only potential of exposure assessed by crude JEM. Comprehensive review of TCE and hydrazine use at the facility.
USA						

	for other chemicals	stand mechanic job and mortality.
Ritz et al., 1999a	Rocket engine testing facility	Retrospective cohort study of cancer incidence and mortality.
USA	Hydrazine and other chemicals 1950-90	Workers with low exposure used as reference instead of unexposed workers.
	Relative intensity of presumptive exposure (4-level scale) by 3 time periods. Time-dependent cumulative exposure score	Dose-response relationship for lung, colorectal, and pancreatic
Rooney et al., 1993	UK Atomic Energy Authority	Case-control study of prostate cancer among UKAEA workers.
UK	13 specific radionuclides 6 metals: Be, Br, Cd, Pb, Hg, Zn; 3 types of chemicals: aromatic, halogenated, other organic compounds; asbestos, metal dusts, metal fumes	No details on JEM. No reporting of exposure results
	For each radionuclides - Level of exposure (none, possible, probable but relatively low, probable but relatively high). For other agents, level of exposure on 3 level scale (none, low, high) Duration of work	Dose-response relationship with radionuclides exposure. No significant findings according to other kinds of exposure
	3 experts consensus based on walkthrough visits, interviews with workers, review of historical facility reports	
	Review of worker's exposure history, year, place, and type of work. 125 work areas classified by health physicists or experienced staff in 7 work environments: Reactor, reactor maintenance, fuel examination after irradiation, fuel fabrication, decontamination and was disposal and laundry, fuel reprocessing.	

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Records of internal

contamination

Carpenter et al., 1988	Y-12 and ORNL	26 chemicals or chemical groups including Be, U, Th, Carbon dusts, welding fumes, cutting oils, hydrazine	Rank of potential exposure to each chemical (0-no, 1-low, 2-moderate, 3-high potential for exposure). Exposure duration=duration of employment in job titles with rank 2 or 3	Subjective evaluation by industrial hygienist of job title/department combination with accounting for time period, review of industrial processes, on-site visits, interview with people, urinalysis and air monitoring data.	Nested case-control of primary CNS cancer. Analyses according to exposure status, exposure duration, employment duration.	No cumulative exposure assessment. No results according to exposure levels. No reference on exposure evaluation report.
USA	1943-79					
Wing et al., 1993	ORNL	Be, Hg, Pb	15 Job categories based on potential for similar occupational environment and activities.	Employment records: Job title, department, payment status and monitoring status for Be, Hg, Pb exposure	To consider the role of possible selection and confounding factors on dose-risk estimators in previous cohort study of solid cancer and leukaemia. No significant changes on dose-risk estimates except Hg	
USA	1943-84		Time spent in job category			

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Ritz, 1999b	Fernald	TCE, kerosene and cutting oils	Exposure level (0 to 3) and duration of exposure (with 15 year lag)	Plant experts: a plant foreman, hygienists, an engineer determined likelihood of chemical exposure for each job title and plant area for 1952-77 period	Cohort study of chemical exposure effects on cancer mortality with accounting for radiation exposure for specific cancer sites.	Good description of highly exposed jobs, jobs with concomitant exposure, cutting oils composition and definition discussed.
USA	FFMPC 1951-90		Internal and external radiation dose			
Ritz at al., 2000	Rocketdyne 1950-94	Internal lung dose Asbestos Hydrazine	Exposure level (0 to 3) defined on job titles. Internal and external radiation dose	? Job titles, employment periods, and job locations used as proxy measures for chemical exposures	Cohort study of internal radiation exposure effect on mortality from specific cancer sites. Dose-response relationship with internal radiation exposure.	Results adjusted for chemical exposure are not shown.
Ruttenber et al., 2001a	Rocky Flats Nuclear weapon facility 1951-1989	Be, CCl4, Cr, Pb, Ni, TCE, PCE, formaldehyde, methylene chloride, asbestos	Time-weighted average (max/min) annual air exposure	Published estimates. For Be, data from a 100s personnel air samplers. Estimates for concentration in breathing zone of workers, adjusted for respirator use	Improving estimates of exposure for epidemiological studies of plutonium workers	Validation of Be exposure estimators. Results in % and Nb of workers exposed to each agent.

Ruttenber et al., 2001b	Rocky Flats	Be, CCl4, Cr, Pb, Ni, TCE, PCE, formaldehyde, methylene chloride, asbestos	Time-weighted average (max/min) daily air concentration. Cumulative exposure for period of interest=Av. concentration x Nb hours worked	Published estimates for similar production process. Hours worked paid/year from employer's roster.	To develop a JEM for epidemiological studies and for determination of eligibility for a medical screening program for highly exposed former workers	No reference of published estimates of exposure levels. No detail on final nb of job groups, on mostly exposed jobs, on 10/20 selected chemicals. Solid estimators allowing accounting for uncertainties. Reporting of exposures according to LOEL
USA	Nuclear weapon facility 1951-1989					
Henn et al., 2007	Chemical laboratories at Y-12, X-10, K-25 and SRS plants 1943-1998	Organic and inorganic chemicals including radioisotopes	Individual cumulative potential exposure indices (PEIs)=Nb of days with task- and time-dependent combination x task- and time-dependent weighting factors	Task-dependent weighting factors determined by industrial hygienists (IH) through jobs review and interviews with workers. Time-dependent weighting factors determined through IH monitoring results.	To assess chemical exposure for a mortality study of 6157 chemical laboratory workers	PEIs are not specific of any chemical. Waiting factor for time were established on the basis of exposure trends data available for only 4 chemicals from 54

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considered

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**Table 2.** Summary of exposure agents evaluated in the job exposure matrix and exposure characteristics of the AREVA NC Pierrelatte plant workers (N=2709)

Exposure agents	Detail	Exposed		Individual cumulative	
		workers	n (%)	exposure score in	exposed workers
				Mean ± SD (Median)	
1-Natural U compounds f*	UF <sub>6</sub> , UF <sub>4</sub> , UO <sub>2</sub> (NO <sub>3</sub> ) <sub>2</sub> , (UO <sub>4</sub> , nH <sub>2</sub> O)	2253 (83.23)		67.49 ± 65.32 (44.50)	
2-Natural U compounds m*	(U <sub>2</sub> O <sub>7</sub> )(NH <sub>4</sub> ) <sub>2</sub> , U <sub>3</sub> O <sub>8</sub> , UO <sub>2</sub> F <sub>2</sub> , UO <sub>3</sub>	1815 (67.05)		42.93 ± 51.01 (23.21)	
3-Natural U compounds s*	UO <sub>2</sub>	992 (36.65)		42.22 ± 40.52 (16.40)	
4-Reprocessed U compounds f*	UF <sub>6</sub> , UF <sub>4</sub> , UO <sub>2</sub> (NO <sub>3</sub> ) <sub>2</sub> , (UO <sub>4</sub> , nH <sub>2</sub> O)	851 (31.44)		31.89 ± 40.52 (16.27)	
5-Reprocessed U compounds m*	(U <sub>2</sub> O <sub>7</sub> )(NH <sub>4</sub> ) <sub>2</sub> , U <sub>3</sub> O <sub>8</sub> , UO <sub>2</sub> F <sub>2</sub> , UO <sub>3</sub>	656 (24.23)		36.62 ± 43.32 (20.53)	
6-Reprocessed U compounds s*	UO <sub>2</sub>	475 (17.55)		35.40 ± 43.76 (17.95)	
7-Chlorinated agents	Perchloroethylene, tetrachloroethene, trichloroethene, dichloromethane, polychlorinated biphenyls (PCBs), carbon tetrachloride	1784 (65.90)		18.49 ± 21.72 (13.37)	
8-Fluoride agents	Fluorhydric acid, tungsten hexafluoride, fluorine, potassium fluoride	1652 (61.03)		28.47 ± 42.39 (13.37)	
9-Nitrogenous agents	Ammonia, ammonia anhydride, nitrogen acid, nitrous	1415 (47.80)		31.55 ± 45.60 (12.04)	



vapours			
10- Solvents containing aromatic hydrocarbons	Benzene, toluene, xylene, styrene	1255 (46.36)	30.41 ± 39.90 (15.26)
11- Welding fumes	Fumes and metal dusts	425 (15.70)	12.07 ± 14.57 (7.78)
12- Vitreous fibres and rock wool	Rock, slag, and glass wools	1280 (47.28)	21.05 ± 26.05 (10.21)
13- Asbestos	Asbestos fireproofing, insulation and braids	1894 (69.97)	19.28 ± 18.73 (15.94)
14- Refractive ceramic fibres		555 (20.50)	9.98 ± 7.93 (8.56)
15- Chromate	Potassium dichromate and chromium trioxide	102 (3.77)	7.56 ± 6.18 (6.42)
16- Chlorine trifluoride		1341 (49.54)	14.94 ± 15.35 (10.04)
17- Trichloroethylene (TCE)		1685 (62.25)	27.27 ± 33.57 (15.25)
18- Lead	Paints, plates and dust	331 (12.23)	8.49 ± 8.32 (6.46)
19- Mercury	Vapours	827 (30.55)	16.46 ± 23.19 (8.96)
20- Silica	Silica gel, silica grains	695 (25.67)	8.71 ± 8.06 (6.73)
21- Hydrazine and other fuels	Hydrazine, domestic fuel, gas-oils, four-star fuel, petroleum	1164 (42.99)	16.18 ± 19.89 (10.29)
22- Heat	Temperature at the workstation > 30°C	2361 (87.22)	54.63 ± 53.71 (34.47)

\* Uranium compounds were classified in terms of absorption types (f-fast, m-moderate or s-slow) according to the Human

Respiratory Tract Model described in ICRP Publication 66 (32)

**Table 3.** AREVA NC Pierrelatte job exposure matrix validity characteristics compared to AREVA NC Pierrelatte workers' medical records used as reference

Exposure category	Observed agreement	Kappa coefficient	Sensitivity	Specificity
Uranium compounds derived from NU*	0.85	0.66	0.81	0.96
Uranium compounds derived from RPU**	0.92	0.83	0.82	0.98
Asbestos	0.61	0.09	1.00	0.60
Vitreous fibres and wools	0.74	0.27	0.50	0.80
Chlorinated agents	0.71	0.42	0.77	0.67
Fluoride agents	0.58	0.15	0.57	0.60
Nitrogenous agents	0.68	0.36	0.59	0.79
Total	0.78	0.56	0.72	0.83

\* Natural uranium

\*\* Reprocessed uranium

**Table 4. Generic jobs with the highest cumulated exposure levels for more than 3 categories of exposure agent.**

Generic Jobs	Exposure agents with the highest scores
Dismantling-decontaminating technician	Compounds derived from RPUF*
	Compounds derived from RPUm*
	Compounds derived from RPU*s*
	TCE
	Fluorinated compounds
	Mercury
	Lead
	Refractive ceramic fibres
Driver at enriched materials chemistry unit	Compounds derived from NUF*
	Compounds derived from NUM*
	TCE
	Fluorinated compounds
	Heat
Mechanic at enriched materials chemistry unit	Compounds derived from NUF*
	Hydrazine and other fuels
	Welding fumes
	Wools
	Heat
Technician and operator at container	Compounds derived from RPUF*

maintenance shop	Compounds derived from RPUm*
	Compounds derived from RPU <sub>s</sub> *
	Fluorinated compounds
Physical-chemistry analysis technician at the plants' main laboratory	Potassium dichromate Mercury
	Nitrogenous compounds
	Silica gel, silica grains

\* Uranium compounds derived from natural (NU) and reprocessed uranium (RPU) were classified in terms of absorption types (f, m or s) according to (ICRP, 1994)

**Table 5.** Correlation between exposure to uranium compounds and other exposure agents. Values of Spearman's rho correlation coefficient (n=2709).

Exposure agents	Asbestos	Ceramic fibres	Chromate	Trichloroethylene	Chlorine trifluoride	Mercury	Lead	Silica	Hydrazine	Chlorinated agents	Fluoride agents	Nitrogenous agents	Solvents	Welding fumes	Wools	Heat
NUF**	<b>0.61*</b>	0.29*	0.10*	<b>0.72*</b>	0.40*	0.31*	0.25*	0.33*	0.24*	<b>0.56*</b>	<b>0.65*</b>	<b>0.52*</b>	0.43*	0.25*	0.26*	<b>0.66*</b>
NUm	0.38*	<b>0.52*</b>	0.20*	0.38*	0.26*	<b>0.53*</b>	0.16*	0.40*	0.19*	0.42*	<b>0.55*</b>	<b>0.59*</b>	0.48*	0.36*	0.47*	0.35*
NUs	0.21*	0.45*	0.31*	0.27*	0.10*	0.40*	0.23*	0.32*	0.17*	0.30*	<b>0.57*</b>	<b>0.65*</b>	<b>0.51*</b>	0.12*	0.24*	0.08*
RPUf	0.03*	0.37*	0.34*	0.10*	-0.01	0.35*	0.16*	<b>0.57*</b>	0.16*	0.26*	0.37*	0.40*	0.27*	0.28*	0.19*	0.03*
RPUm	-0.08*	0.44*	0.36*	-0.05	-0.04	0.08*	0.23*	0.35*	0.14*	0.15*	0.40*	0.46*	0.23*	0.12*	0.17*	0.01*
RPU s	0.10*	0.37*	0.35*	0.16*	0.11*	0.26*	0.27*	0.31*	0.32*	0.22*	0.40*	0.47*	0.34*	0.03*	0.20*	0.07*

\*Two-tailed significance test p value <0.01.

\*\* Uranium compounds derived from natural (NU) and reprocessed uranium (RPU) were classified in terms of absorption types (f, m or s). Values of rho > 0.50 corresponding to a large correlation according to Cohen's criteria are bolded.