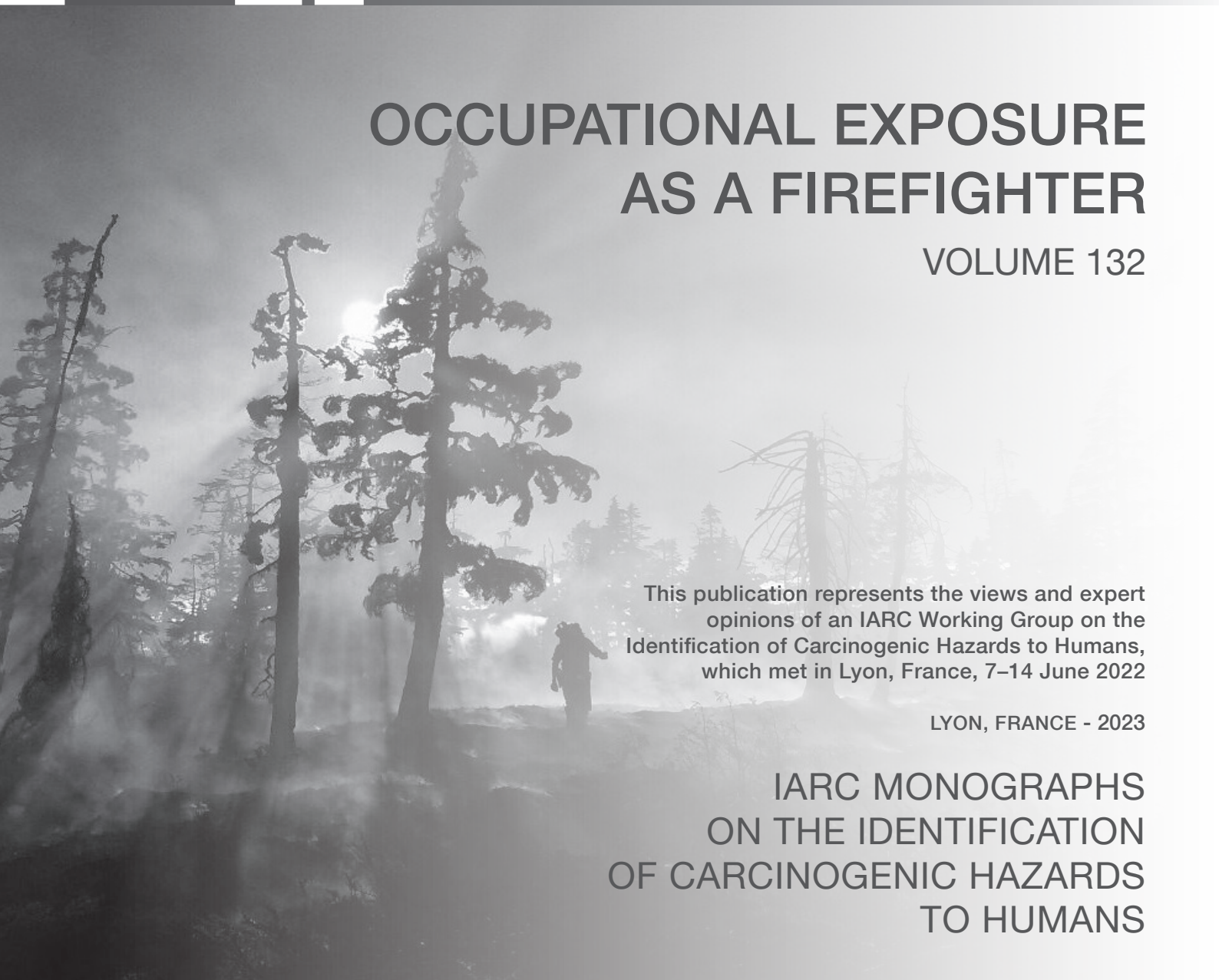
IARC MONOGRAPHS



OCCUPATIONAL EXPOSURE AS A FIREFIGHTER

VOLUME 132

This publication represents the views and expert opinions of an IARC Working Group on the Identification of Carcinogenic Hazards to Humans, which met in Lyon, France, 7–14 June 2022

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IARC MONOGRAPHS ON THE IDENTIFICATION OF CARCINOGENIC HAZARDS TO HUMANS

International Agency for Research on Cancer

World Health Organization

Table S1.25 Biomarkers of exposure other than fire smoke and polycyclic aromatic hydrocarbons

Sample type	Type of fire	Location, sampling date	Sampling period and duration	No. of individuals sampled and type of firefighter	No. of samples	Mean ± SD *geometric mean (± GSD or 95% CI) **median (range)	Units	LOD and/or LOQ	Comments and other relevant information	Reference
Asbestos										
Radiograph	NA	New York City, USA	NA	212 municipal firefighters	212	Pleural/parenchymal abnormalities	NA	NA	Mixed biomarker of exposure and effect	Markowitz et al. (1991)
Chemical flame retardants: polybrominated diphenyl ethers (PBDEs) and other brominated flame retardants										
Serum	NA	California, USA, 2009	NA	12 veteran municipal firefighters (11 male)	12	BDE-28: 2 ± 3 BDE-47: 52 ± 70 BDE-99: 10 ± 11 BDE-100: 12 ± 16 BDE-153: 33 ± 32 BDE-209: 27 ± 24	ng/g lipid	NR	Blood collected post-fire	Shaw et al. (2013)
Serum	NA	California, USA, 2010-2011	NA	101 (99 male) municipal firefighters	101	BDE-28: 1.7 (1.5–1.93)* BDE-47: 32.3 (27.8–37.5)* BDE-99: 6.19 (5.35–7.17)* BDE-100: 5.68 (4.77–6.75)* BDE-153: 15.4 (12.9–18.3)* BDE-209: 29% detection	ng/g lipid	0.003–0.15 ng/mL		Park et al. (2015)
Serum	Controlled residential fires	Illinois, USA, 2015	Before and after fires	36 firefighters (32 male career and volunteer, mostly from midwest)	36	*Post-fire concentrations* BDE-28: 0.54 ± 2.15* BDE-47: 8.37 ± 2.57* BDE-99: 1.49 ± 2.76* BDE-100: 1.67 ± 2.28* BDE-153: 5.53 ± 2.44* BDE-209: 3.01 ± 1.57*	ng/g lipid	NR	Serum concentrations at 23-h post-fire provided here. No evidence of pre- to 23-h post-fire increase in PBDE metabolites	Mayer et al. (2021)

Table S1.25 (continued)

Sample type	Type of fire	Location, sampling date	Sampling period and duration	No. of individuals sampled and type of firefighter	No. of samples	Mean ± SD *geometric mean (± GSD or 95% CI) **median (range)	Units	LOD and/or LOQ	Comments and other relevant information	Reference
Serum	NA	Busan, Republic of Korea, 2020	NA	92 male Busan firefighters	92	Sum 27 PBDE congeners: 17.1 (range, 1.58–95.2)	ng/g lipid	0.0013–0.399	The summed concentration of PBDEs in firefighters was higher than in the general population, and there was a positive correlation in the firefighters between PBDE levels and duration of service	Ekpe et al. (2021)
Polychlorinated and polybrominated dibenzo-para-*dioxins and dibenzofurans (PCDD/Fs and PBDD/Fs)*										
Serum	NA	Taiwan, China, 2010	NA	20 (16 firefighters and 4 fire investigators)	20	*IARC Group 1* 2,3,7,8-TCDD: 1.4 ± 0.45 2,3,4,7,8-PeCDF: 8.0 ± 2.3 *Selected others* 1,2,3,7,8-PeCDD: 5.8 ± 2.6 1,2,3,6,7,8-HxCDD: 8.8 ± 4.8 1,2,3,4,6,7,8-HpCDD: 14 ± 8.1 OCDD: 250 ± 150 1,2,3,4,6,7,8-HpCDF: 6.9 ± 4.3 OCDF: 1.6 ± 1.2	pg/g lipid	NR	Fire investigators had median TEQs higher the general Taiwanese male population	Hsu et al. (2011)

Table S1.25 (continued)

Sample type	Type of fire	Location, sampling date	Sampling period and duration	No. of individuals sampled and type of firefighter	No. of samples	Mean ± SD *geometric mean (± GSD or 95% CI) **median (range)	Units	LOD and/or LOQ	Comments and other relevant information	Reference
Serum	NA	Eastern Siberia, Russian Federation	NA	13 current firefighters	13	1,2,3,4,6,7,8-HpCDD: 13.1 (range, 4.6–46.8) 1,2,3,7,8,9-HxCDF: 1.7 (range, 0.5–3.3) OCDF: 5.8 (range, 1.4–8.9)	pg/g lipid	NR	HpCDD and HxCDF levels were higher in current firefighters than non-firefighters and OCDF was higher in current firefighters than former firefighters and non-firefighters	Chernyak et al. (2012)
Serum	NA	California, USA, 2009	NA	12 veteran municipal firefighters (11 male)	12	1,2,3,6,7,8-HxCDD: 33 ± 25 1,2,3,4,6,7,8-HpCDD: 87 ± 51 OCDD: 250 ± 180 1,2,3,4,6,7,8-HpCDF: 78 ± 119 2,3,7,8-TBDD: 58 ± 134 2,3,4,7,8-PeBDF: 126 ± 312 1,2,3,7,8-PeBDF: 126 ± 303 OBDF: 2987 ± 1755	pg/g lipid	NR	Blood collected post-fire. Firefighters had higher HpCDD concentrations than did general US population	Shaw et al. (2013)

Table S1.25 (continued)

Sample type	Type of fire	Location, sampling date	Sampling period and duration	No. of individuals sampled and type of firefighter	No. of samples	Mean ± SD *geometric mean (± GSD or 95% CI) **median (range)	Units	LOD and/or LOQ	Comments and other relevant information	Reference
Serum	Controlled residential fires	Illinois, USA, 2015	Before and after fires	9 firefighters (mostly from midwest)	9	*Post-fire concentrations:* *IARC Group 1* 2,3,7,8-TCDD: 0.75 ± 1.12* 2,3,4,7,8-PeCDF: NR *Selected others* 1,2,3,7,8-PeCDD: 2.49 ± 1.11* 1,2,3,6,7,8-HxCDD: 12.5 ± 1.15* 1,2,3,4,6,7,8-HpCDD: 15.7 ± 1.13* OCDD: 91.7 ± 1.19* 1,2,3,4,6,7,8-HpCDF: 6.09 ± 1.20* OCDF: NR	pg/g lipid	NR	Concentrations at 23-h post-fire provided here. Concentrations were near or below those for general US population levels. No evidence of an increase from before to 23 h after the fire	Mayer et al. (2021)
Polychlorinated biphenyls (PCBs)										
Serum	NA	Eastern Siberia, Russian Federation	NA	13 current firefighters	13	PCB-105: 11.37 (range, 5.03–32.55) PCB-118: 41.39 (range, 16.35–105.76) PCB-157: 4.29 (range, 1.63–11.78) PCB-167: 3.28 (range, 1.02–8.22)	ng/g lipid	NR	PCB-105 and PCB-118 higher in current firefighters than in non-firefighters. PCB-157 and PCB-167 higher in current (and former) firefighters than in non-firefighters	Chernyak et al. (2012)
Serum	NA	California, USA, 2009	NA	12 veteran municipal firefighters (11 male)	12	*IARC Group 1* PCB-105: 1 ± 1 PCB-118: 4 ± 2 PCB-156: 5 ± 4 ∑PCBs: 135 ± 91	ng/g lipid	NR	Sum of PCB concentrations for firefighters collected post-fire were lower than those for the general US population	Shaw et al. (2013)

Table S1.25 (continued)

Sample type	Type of fire	Location, sampling date	Sampling period and duration	No. of individuals sampled and type of firefighter	No. of samples	Mean ± SD *geometric mean (± GSD or 95% CI) **median (range)	Units	LOD and/or LOQ	Comments and other relevant information	Reference
Serum	NA	California, USA, 2010–2011	NA	101 (99 male) municipal firefighters	101	PCB-66: 1.17 (1.09–1.25)* PCB-74: 1.77 (1.61–1.95)* PCB-99: 1.76 (1.61–1.93)* PCB-118: 2.66 (2.46–2.87)* PCB-138: 5.53 (4.98–6.15)* PCB-153: 12.2 (10.8–13.7)* PCB-156: 1.84 (1.61–2.09)* PCB-170: 3.64 (3.16–4.19)* PCB-180: 13.4 (11.7–15.4)* PCB-183: 1.03 (0.93–1.15)* PCB-187: 2.99 (2.61–3.42)* PCB-194: 3.37 (2.89–3.93)* PCB-203: 3.37 (2.92–3.89)*	ng/g lipid	0.01 ng/g lipid	Serum PCBs were lower than in the 2003–2004 NHANES comparison group	Park et al. (2015)
Chemical flame retardants: organophosphate flame retardants (OPFRs)										
Urine	Controlled structure training fires with modern furnishings	Chicago, Illinois, USA, 2010–2011	~20-min or 3-h training fires	146 firefighters	146	TCEP (BCEtP): 0.86 (ND–10)** TCPP (BCPP): 0.24 (ND–2.9)** TDCPP (BDCPP): 3.4 (0.30–44)** TBP (DBuP): 0.18 (ND–2.4)** TPP (DPhP): 2.9 (0.24–28)**	ng/mL	0.05–0.16	Concentrations in firefighters generally higher than in the general public in Atlanta, USA, collected in 2015	Jayatilaka et al. (2017)

Table S1.25 (continued)

Sample type	Type of fire	Location, sampling date	Sampling period and duration	No. of individuals sampled and type of firefighter	No. of samples	Mean ± SD *geometric mean (± GSD or 95% CI) **median (range)	Units	LOD and/or LOQ	Comments and other relevant information	Reference
Urine	Controlled residential fires	Illinois, Wisconsin and Indiana, USA, 2015	Before and after fires	36 firefighters (32 male career and volunteer, mostly from midwest)	36	*Post-fire concentrations:* TCEP (BCEtP): 1.67 ± 1.94* TDCPP (BDCPP): 2.7 ± 1.97* TPP (DPhP): 0.34 ± 2.09*	µg/g creatinine	0.08–0.16	3-h post-fire urine concentrations provided here. Significant increase from pre to post-fire found for BCEtP and DPhP	Mayer et al. (2021)
Per and poly-fluoroalkyl substances (PFAS)										
Serum	NA	California, USA, 2009	NA	12 veteran municipal firefighters (11 male)	12	*IARC Group 2B* PFOA: 7 ± 3 *Selected others* PFOS: 12 ± 15 PFHxS: 1 ± 1 PFNA: 2 ± 1	ng/mL	NR	Concentrations of PFOA and PFNA were higher, and PFOS and PFHxS were lower in firefighters than in 2013–2014 NHANES participants	Shaw et al. (2013)
Serum	NA	Phoenix and Tucson, Arizona, USA 2009	NA	38	38	PFHxS: 3.07 (2.66–3.55)* PFOS: 13.36 (11.64–15.34)* PFOA: 3.33 (2.89–3.84)* PFNA: 0.93 (0.81–1.06)* PFDA: 0.25 (0.22–0.29)* PFUnDA: 0.12 (0.10–0.14)* Me-FOSAA: 0.21 (0.17–0.26)*	ng/mL	0.1–0.2	Comparing 38 Arizona firefighters and 49 NHANES 2009–2010 participants, firefighters had elevated PFHxS and lower PFNA and PFUnDA	Khalil et al. (2020)

Table S1.25 (continued)

Sample type	Type of fire	Location, sampling date	Sampling period and duration	No. of individuals sampled and type of firefighter	No. of samples	Mean ± SD *geometric mean (± GSD or 95% CI) **median (range)	Units	LOD and/or LOQ	Comments and other relevant information	Reference
Serum	Training fires burning jet fuel and wooden pallets, Sthamex 3% AFFF used for fire suppression	Oulu Airport, Finland 2010	Two 60–63-minute training sessions daily for 3 days over a 3-mo period	Blood samples collected at baseline and 2 wk after each training session in 8 airport firefighters	32	*Post-exposure concentrations:* PFHxS: 2.19 (1.05–4.30)** PFOS: 11.1 (2.8–35.8)** PFOA: 2.94 (1.61–4.85)** PFNA: 1.22 (0.43–6.69)**	ng/mL	0.35	PFHxS and PFNA concentrations increased after three consecutive training sessions, statistical analysis NR	Laitinen et al. (2014)
Serum	NA	Ohio and West Virginia, USA 2005–2006	NA	8826 male adults, including 37 firefighters	36	PFHxS: 4.60 (0.25–14.60)** PFOS: 27.85 (0.25–67.50)** PFOA: 31.50 (0.25–75.35)** PFNA: 1.60 (0.25–4.40)**	ng/mL	NR	Concentration of PFHxS was significantly higher in firefighters than in non-firefighters	Jin et al. (2011)
Serum	NA	Southern California firefighters 2010–2011	NA	101	101	PFOS: 12.50 (11.34–13.78)* PFOA: 3.75 (3.37–4.17)* PFHxS: 2.26 (2.00–2.54)* PFNA: 1.15 (1.06–1.25)* PFDA: 0.90 (0.78–1.03)* PFHpA: 0.90 (0.78–1.03)* PFOSA: 0.032 (0.027–0.037)* Me-FOSAA: 0.16 (0.13–0.18)* Et-FOSAA: 0.016 (0.014–0.018)*	ng/mL	0.01–0.22 ng/mL	PFDA concentrations higher in firefighters than in NHANES 2009 participants. PFHpA concentrations increased with use of class A firefighting foam	Dobraca et al. (2015)

Table S1.25 (continued)

Sample type	Type of fire	Location, sampling date	Sampling period and duration	No. of individuals sampled and type of firefighter	No. of samples	Mean ± SD *geometric mean (± GSD or 95% CI) **median (range)	Units	LOD and/or LOQ	Comments and other relevant information	Reference
Serum	NA	Queensland, Australia, 2013	NA	20 firefighters with 19–38 yr of exposure to AFFF	20	PFOS: NR (92–343) PFHxS: NR (49–326)	ng/mL	PFOS, 0.02 PFHxS, 0.07	PFOS and PFHxS concentrations were markedly elevated in firefighters compared with 19 university students and office workers, samples collected in 2011–2012	Rotander et al. (2015a)
Serum	NA	Australia, 2013	NA	149 firefighters who used AFFF	149	*IARC Group 2B* PFOA: 4.6 ± 2.4 *Selected others* PFOS: 74 ± 61 PFHxS: 33 ± 36 PFNA: 0.76 ± 0.3	ng/mL	0.02–0.06	Lower PFOS concentrations in newer firefighters who did not use PFOS-containing AFFF	Rotander et al. (2015b)
Serum	NA	San Francisco, California, USA, 2014–2015	NA	86 female municipal firefighters	86	*IARC Group 2B* PFOA: 1.15 (1.05–1.25)* *Selected others* PFOS: 4.11 (3.68–4.59)* PFHxS: 3.79 (3.24–4.43)* PFNA: 0.67 (0.61–0.74)* PFUnDA: 0.18 (0.14–0.22)* PFDA 0.25 (0.23–0.28)	ng/mL	0.05–0.1	Firefighters had higher PFHxS, PFUnDA, and PFNA concentrations than did office workers. Firefighters and officers had higher PFNA, PFOA, PFDA, and PFUnDA concentrations than did drivers	Trowbridge et al. (2020)

Table S1.25 (continued)

Sample type	Type of fire	Location, sampling date	Sampling period and duration	No. of individuals sampled and type of firefighter	No. of samples	Mean ± SD *geometric mean (± GSD or 95% CI) **median (range)	Units	LOD and/or LOQ	Comments and other relevant information	Reference
Serum	NA	Ohio, USA, 2018–2019	NA	47 male airport and suburban firefighters	45	*IARC Group 2B* PFOA: 2.17 (1.10–4.65)** *Selected others* PFOS: 10.7 (4.28–30.4)** PFHxS: 6.45 (2.2–12.3)** PFNA: 0.45 (0.22–1.36)**	ng/mL	NR	PFHxS was elevated in firefighters compared with NHANES 2015–2016 participants. PFOS higher in airport than suburban firefighters	Leary et al. (2020)
Serum	NA	New Jersey, USA 2019	NA	116 volunteer firefighters	116	PFHxS: 1.83 (1.61–2.09)* PFOS: 4.25 (3.76–4.80)* PFOA: 2.07 (1.89–2.26)* PFNA: 0.97 (0.89–1.05)* PFDA: 0.31 (0.29–0.33)* PFDoA: 0.14 (0.13–0.15)* PFUnDA: 0.11 (0.10–0.12)* Me-FOSAA: 0.08 (0.07–0.09)*	ng/mL	0.1	PFDoA, PFNA, and PFDA concentrations were elevated in firefighters compared with NHANES 2015–2018 participants. PFDoA and PFDA were positively associated with years of firefighting	Graber et al. (2021)
Heavy metals										
Serum	NR, multiple types	Saudi Arabia (two regions), NR	Within 1 h after firefighting	49 male firefighters	24–27	*Stratified by two regions:* *IARC Group 1* Cadmium: 0.7 ± 0.3 and 1.0 ± 0.8 Arsenic: 3.4 ± 2.3 and 3.3 ± 1.5 *Other* Antimony: ND Lead: 34.9 ± 10.6 and 38.3 ± 16.4	µg/L	NR	No significant difference compared with control participants	Al-Malki (2009)

Table S1.25 (continued)

Sample type	Type of fire	Location, sampling date	Sampling period and duration	No. of individuals sampled and type of firefighter	No. of samples	Mean ± SD *geometric mean (± GSD or 95% CI) **median (range)	Units	LOD and/or LOQ	Comments and other relevant information	Reference
Blood	Wildland	Western USA, 2007–2009	Pre- and post-season	66 firefighters (41 with pre- and post-season blood draws)		In the 2009 season, only 1 of 31 firefighters had a measurable mercury level pre- or post-season	µg/L	4	No significant difference compared with control participants	Smith et al. (2013)
Blood	NA	California, USA, 2011	NA	101 firefighters (99 male)	101	*IARC Group 1* Cadmium: 0.19 (0.18–0.21)* *Selected others* Lead: 9.6 (8.7–10.5)* Mercury: 2.79 (2.36–3.30)* Manganese: 7.61 (7.26–7.98)*	µg/L	0.06–0.54	Only blood concentrations of mercury were above general population levels	Dobraca et al. (2015)
Blood	NA	Dammam city, Saudi Arabia	NA	50	50	*IARC Group 1* Cadmium: 0.24 ± 0.04 *Selected others* Antimony: 0.006 ± 0.002 Lead: 3.03 ± 1.09 Mercury: 0.41 ± 0.67	µg/dL	NR	No significant difference comparing firefighters with 50 controls	Salama & Bashawri (2017)

Table S1.25 (continued)

Sample type	Type of fire	Location, sampling date	Sampling period and duration	No. of individuals sampled and type of firefighter	No. of samples	Mean ± SD *geometric mean (± GSD or 95% CI) **median (range)	Units	LOD and/or LOQ	Comments and other relevant information	Reference
Blood	Structure fire (Notre Dame Cathedral)	Paris, France, 2019	Initial blood sample 2–3 weeks after response	168 structural [municipal] firefighters (164 male)	168	Lead: 31.5 (27.7–35.9)*	µg/L	0.2	Initially, 42 firefighters > 50 µg/L; 1 mo later, 16 firefighters > 50 µg/L; 6 mo later, 3 firefighters > 50 µg/L	Allonneau et al. (2021)

AFFF, aqueous film-forming foam; BCEtP, bis(2-chloroethyl) phosphate; BCPP, bis-(1-chloro-2-propyl) phosphate; BDCPP, bis(1,3-dichloro-2-propyl)phosphate; BDE, brominated diphenyl ether; CI, confidence interval; DBuP, di-*n*-butyl phosphate; DPhP, diphenyl phosphate; Et-FOSAA, 2-(*N*-ethyl-perfluorooctanesulfonamido) acetic acid; FR, flame retardant; GSD, geometric standard deviation; HpCDD, heptachlorodibenzo-*para*-dioxins; HpCDF, 1,2,3,4,6,8,9-heptachlorodibenzofuran; HxCDD, 1,2,3,7,8,9-hexachlorodibenzo-*para*-dioxin; HxCDF, 1,2,4,6,8,9-hexachlorodibenzofuran; LOD, limit of detection; LOQ, limit of quantification; Me-FOSAA, 2-(*N*-methyl-perfluorooctanesulfonamido) acetic acid; mo, month; NA, not applicable; ND, not detected; NHANES, National Health and Nutrition Examination Survey; NR, not reported; OBDF, 1,2,3,4,6,7,8,9-octabromodibenzofuran; OCDD, octachlorodibenzodioxine; OCDF, 1,2,3,4,6,7,8,9-octachlorodibenzofuran; OPFR, organophosphate flame retardant; PAH, polycyclic aromatic hydrocarbon; PBDD/F, polybrominated dibenzo-*para*-dioxins and dibenzofurans; PBDE, polybrominated diphenyl ether; PCB, polychlorinated biphenyl; PCDD/F, polychlorinated dibenzo-*para*-dioxins and dibenzofurans; PeBDF, 1,2,3,7,8-pentabromodibenzofuran; 1,2,3,7,8-PeCDD, 1,2,3,7,8-pentachlorodibenzo-*para*-dioxin; 2,3,4,7,8-PeCDF, 2,3,4,7,8-pentachlorodibenzofuran; PFAS, per- and polyfluoroalkyl substances; PFDA, perfluorodecanoic acid; PFDoA, perfluorododecanoic acid; PFHpA, perfluoroheptanoic acid; PFHxS, perfluorohexanesulfonic acid; PFNA, perfluorononanoic acid; PFOA, perfluorooctanoic acid; PFOS, perfluorooctane sulfonate; PFOSA, perfluorooctane sulfonamide; PFUnDA, perfluoroundecanoic acid; SD, standard deviation; TBP, tributyl phosphate; 2,3,7,8-TCDD, 2,3,7,8-tetrachlorodibenzo-*para*-dioxin; TCEP, tris(2-carboxyethyl) phosphate; TCPP, tris(2-chloropropyl) phosphate; TDCPP, tris(1,3-dichloro-2-propyl)phosphate; TEQ, toxic equivalent quantity; TPP, triphenyl phosphate; wk, week.

References

Adetona AM, Adetona O, Gogal RM Jr, Diaz-Sanchez D, Rathbun SL, Naeher LP (2017). Impact of work task-related acute occupational smoke exposures on select proinflammatory immune parameters in wildland firefighters. *J Occup Environ Med*. 59(7):679–90. doi:10.1097/JOM.0000000000001053 PMID:28692002

Adetona AM, Martin WK, Warren SH, Hanley NM, Adetona O, Zhang JJ, et al. (2019). Urinary mutagenicity and other biomarkers of occupational smoke exposure of wildland firefighters and oxidative stress. *Inhal Toxicol*. 31(2):73–87. doi:10.1080/08958378.2019.1600079 PMID:30985217

Adetona O, Dunn K, Hall DB, Achtemeier G, Stock A, Naeher LP (2011). Personal $PM_{2.5}$ exposure among wildland firefighters working at prescribed forest burns in southeastern United States. *J Occup Environ Hyg*. 8(8):503–11. doi:10.1080/15459624.2011.595257 PMID:21762011

Adetona O, Simpson CD, Onstad G, Naeher LP (2013a). Exposure of wildland firefighters to carbon monoxide, fine particles, and levoglucosan. *Ann Occup Hyg*. 57(8):979–91. doi:10.1093/annhyg/met024 PMID:23813888

Adetona O, Zhang JJ, Hall DB, Wang JS, Vena JE, Naeher LP (2013b). Occupational exposure to woodsmoke and oxidative stress in wildland firefighters. *Sci Total Environ*. 449:269–75. doi:10.1016/j.scitotenv.2013.01.075 PMID:23434577

Akhtar US, Keir JL, Matschke D, White P, Blais JM (2016). Occupational exposure to polycyclic aromatic hydrocarbons (PAHs) by firefighters. *Toxicol Lett*. 259:S211. doi:10.1016/j.toxlet.2016.07.505

Al-Malki AL (2009). Serum heavy metals and hemoglobin related compounds in Saudi Arabia firefighters. *J Occup Med Toxicol*. 4(1):18. doi:10.1186/1745-6673-4-18 PMID:19583874

Alharbi BH, Pasha MJ, Al-Shamsi MAS (2021). Firefighter exposures to organic and inorganic gas emissions in emergency residential and industrial fires. *Sci Total Environ*. 770:145332. doi:10.1016/j.scitotenv.2021.145332 PMID:33515879

Allonneau A, Mercier S, Maurin O, Robardet F, Menguy-Fleuriot A, Luu SC, et al. (2021). Lead contamination among Paris Fire Brigade firefighters who fought the Notre Dame Cathedral fire in Paris. *Int J Hyg Environ Health*. 233:113707. doi:10.1016/j.ijheh.2021.113707 PMID:33631659

Andersen MHG, Saber AT, Pedersen PB, Loft S, Hansen ÅM, Koponen IK, et al. (2017). Cardiovascular health effects following exposure of human volunteers during fire extinction exercises. *Environ Health*. 16(1):96. doi:10.1186/s12940-017-0303-8 PMID:28877717

Anthony TR, Joggerst P, James L, Burgess JL, Leonard SS, Shogren ES (2007). Method development study for APR cartridge evaluation in fire overhaul exposures. *Ann Occup Hyg*. 51(8):703–16. doi:10.1093/annhyg/mem048 PMID:17989124

Austin CC, Wang D, Ecobichon DJ, Dussault G (2001a). Characterization of volatile organic compounds in smoke at experimental fires. *J Toxicol Environ Health A*. 63(3):191–206. doi:10.1080/15287390151101547 PMID:11405415

Austin CC, Wang D, Ecobichon DJ, Dussault G (2001b). Characterization of volatile organic compounds in smoke at municipal structural fires. *J Toxicol Environ Health A*. 63(6):437–58. doi:10.1080/152873901300343470 PMID:11482799

Australian Government Productivity Commission (2022). Report on Government Services 2022. Emergency services for fire and other events. Available from: https://www.pc.gov.au/research/ongoing/report-on-government-services/2022/emergency-management, accessed June 2022.

Banks APW, Thai P, Engelsman M, Wang X, Osorio AF, Mueller JF (2021a). Characterising the exposure of Australian firefighters to polycyclic aromatic hydrocarbons generated in simulated compartment fires. *Int J Hyg Environ Health*. 231:113637. doi:10.1016/j.ijheh.2020.113637 PMID:33080523

Banks APW, Wang X, Engelsman M, He C, Osorio AF, Mueller JF (2021b). Assessing decontamination and laundering processes for the removal of polycyclic aromatic hydrocarbons and flame retardants from firefighting uniforms. *Environ Res*. 194:110616. doi:10.1016/j.envres.2020.110616 PMID:33321140

Barboni T, Cannac M, Pasqualini V, Simeoni A, Leoni E, Chiaramonti N (2010). Volatile and semi-volatile organic compounds in smoke exposure of firefighters during prescribed burning in the Mediterranean region. *Int J Wildland Fire*. 19(5):606. doi:10.1071/WF08121

Barnard RJ, Weber JS (1979). Carbon monoxide: a hazard to fire fighters. *Arch Environ Health*. 34(4):255–7. doi:10.1080/00039896.1979.10667410 PMID:475470

Baxter CS, Hoffman JD, Knipp MJ, Reponen T, Haynes EN (2014). Exposure of firefighters to particulates and polycyclic aromatic hydrocarbons. *J Occup Environ Hyg*. 11(7):D85–91. doi:10.1080/15459624.2014.890286 PMID:24512044

Baxter CS, Ross CS, Fabian T, Borgerson JL, Shawon J, Gandhi PD, et al. (2010). Ultrafine particle exposure during fire suppression–is it an important contributory factor for coronary heart disease in firefighters? *J Occup Environ Med*. 52(8):791–6. doi:10.1097/JOM.0b013e3181ed2c6e PMID:20657302

Bolstad-Johnson DM, Burgess JL, Crutchfield CD, Storment S, Gerkin R, Wilson JR (2000). Characterization of firefighter exposures during fire overhaul. *AIHAJ*. 61(5):636–41. doi:10.1080/15298660008984572 PMID: 11071414

Bott RC, Kirk KM, Logan MB, Reid DA (2017). Diesel particulate matter and polycyclic aromatic hydrocarbons in fire stations. *Environ Sci Process Impacts*. 19(10):1320–6. doi:10.1039/C7EM00291B PMID:28861557

Brandt-Rauf PW, Cosman B, Fallon LF Jr, Tarantini T, Idema C (1989). Health hazards of firefighters: acute pulmonary effects after toxic exposures. *Br J Ind Med*. 46(3):209–11. doi:10.1136/oem.46.3.209 PMID:2930733

Brandt-Rauf PW, Fallon LF Jr, Tarantini T, Idema C, Andrews L (1988). Health hazards of fire fighters: exposure assessment. *Br J Ind Med*. 45(9):606–12. doi:10.1136/oem.45.9.606 PMID:3179235

Bridgman S (2001). Community health risk assessment after a fire with asbestos containing fallout. *J Epidemiol Community Health*. 55(12):921–7. doi:10.1136/jech.55.12.921 PMID:11707487

Burgess JL, Crutchfield CD (1995). Tucson fire fighter exposure to products of combustion: a risk assessment. *Appl Occup Environ Hyg*. 10(1):37–42. doi:10.1080/1047322X.1995.10387609

Burgess JL, Nanson CJ, Bolstad-Johnson DM, Gerkin R, Hysong TA, Lantz RC, et al. (2001). Adverse respiratory effects following overhaul in firefighters. *J Occup Environ Med*. 43(5):467–73. doi:10.1097/00043764-200105000-00007 PMID:11382182

Burgess JL, Nanson CJ, Hysong TA, Gerkin R, Witten ML, Lantz RC (2002). Rapid decline in sputum IL-10 concentration following occupational smoke exposure. *Inhal Toxicol*. 14(2):133–40. doi:10.1080/089583701753403953 PMID:12122576

Caban-Martinez AJ, Kropa B, Niemczyk N, Moore KJ, Baum J, Solle NS, et al. (2018). The "warm zone" cases: environmental monitoring immediately outside the fire incident response arena by firefighters. *Saf Health Work*. 9(3):352–5. doi:10.1016/j.shaw.2017.12.003 PMID: 30370169

Caban-Martinez AJ, Louzado-Feliciano P, Santiago KM, Baum J, Schaefer Solle N, Rivera G, et al. (2020). Objective measurement of carcinogens among Dominican Republic firefighters using silicone-based wristbands. *J Occup Environ Med*. 62(11):e611–5. doi:10.1097/JOM.0000000000002006 PMID:32826549

Carballo Leyenda B, Rodríguez-Marroyo JA, López-Satué J, Avila Ordás C, Pernía Cubillo R, Villa Vicente JG (2010). [Exposure to carbon monoxide in wildland firefighters during wildfires suppression]. *Rev Esp Salud Pública*. 84(6):799–807. [Spanish]doi:10.1590/S1135-57272010000600010 PMID:21327314

Chernyak YI, Shelepchikov AA, Brodsky ES, Grassman JA (2012). PCDD, PCDF, and PCB exposure in current and former firefighters from Eastern Siberia. *Toxicol Lett*. 213(1):9–14. doi:10.1016/j.toxlet.2011.09.021 PMID: 21979175

Cherry N, Aklilu YA, Beach J, Britz-McKibbin P, Elbourne R, Galarneau JM, et al. (2019). Urinary 1-hydroxypyrene and skin contamination in firefighters deployed to the Fort McMurray fire. *Ann Work Expo Health*. 63(4):448–58. doi:10.1093/annweh/wxz006 PMID:30753267

Cherry N, Galarneau JM, Kinniburgh D, Quemerais B, Tiu S, Zhang X (2021a). Exposure and absorption of PAHs in wildland firefighters: a field study with pilot interventions. *Ann Work Expo Health*. 65(2):148–61. doi:10.1093/annweh/wxaa064 PMID:32572446

Chung J, Demers PA, Kalenge S, Kirkham TL (2020). Career fire hall exposures to diesel engine exhaust in Ontario, Canada. *J Occup Environ Hyg*. 17(1):38–46. doi:10.1080/15459624.2019.1691729 PMID:31851590

Cone DC, MacMillan DS, Van Gelder C, Brown DJ, Weir SD, Bogucki S (2005). Noninvasive fireground assessment of carboxyhemoglobin levels in firefighters. *Prehosp Emerg Care*. 9(1):8–13. doi:10.1080/10903120590891912 PMID:16036821

CTIF (2021). World Fire Statistics. Report No. 26. International Association of Fire and Rescue Services. Available from: https://ctif.org/sites/default/files/2021-06/CTIF_Report26.pdf, accessed June 2022.

De Vos AJ, Cook A, Devine B, Thompson PJ, Weinstein P (2006). Effect of protective filters on fire fighter respiratory health during simulated bushfire smoke exposure. *Am J Ind Med*. 49(9):740–50. doi:10.1002/ajim.20369 PMID:16847937

De Vos AJ, Cook A, Devine B, Thompson PJ, Weinstein P (2009a). Effect of protective filters on fire fighter respiratory health: field validation during prescribed burns. *Am J Ind Med*. 52(1):76–87. doi:10.1002/ajim.20651 PMID:18946878

De Vos AJ, Reisen F, Cook A, Devine B, Weinstein P (2009b). Respiratory irritants in Australian bushfire smoke: air toxics sampling in a smoke chamber and during prescribed burns. *Arch Environ Contam Toxicol*. 56(3):380–8. doi:10.1007/s00244-008-9209-3 PMID:18712497

Dietrich J, Yermakov M, Reponen T, Kulkarni P, Qi C, Grinshpun SA (2015). Protection of firefighters against combustion aerosol particles: simulated workplace protection factor of a half-mask respirator (pilot study). *J Occup Environ Hyg*. 12(6):415–20. doi:10.1080/15459624.2015.1006637 PMID:25625543

Dobraca D, Israel L, McNeel S, Voss R, Wang M, Gajek R, et al. (2015). Biomonitoring in California firefighters: metals and perfluorinated chemicals. *J Occup Environ Med*. 57(1):88–97. doi:10.1097/JOM.0000000000000307 PMID:25563545

Dunn KH, Devaux I, Stock A, Naeher LP (2009). Application of end-exhaled breath monitoring to assess carbon monoxide exposures of wildland firefighters at prescribed burns. *Inhal Toxicol*. 21(1):55–61. doi:10.1080/08958370802207300 PMID:18946764

Dunn KH, Shulman S, Stock AL, Naeher LP (2013). Personal carbon monoxide exposures among firefighters at prescribed forest burns in the southeastern United States. *Arch Environ Occup Health*. 68(1):55–9. doi:10.1080/19338244.2011.633126 PMID:23298425

Easter E, Lander D, Huston T (2016). Risk assessment of soils identified on firefighter turnout gear. *J Occup Environ Hyg*. 13(9):647–57. doi:10.1080/15459624.2016.1165823 PMID:27027971

Edwards R, Johnson M, Dunn KH, Naeher LP (2005). Application of real-time particle sensors to help mitigate exposures of wildland firefighters. *Arch Environ Occup Health*. 60(1):40–3. doi:10.3200/AEOH.60.1.40-43 PMID:16961007

Ekpe OD, Sim W, Choi S, Choo G, Oh JE (2021). Assessment of exposure of Korean firefighters to polybrominated diphenyl ethers and polycyclic aromatic hydrocarbons via their measurement in serum and polycyclic aromatic hydrocarbon metabolites in urine. *Environ Sci Technol*. 55(20):14015–25. doi:10.1021/acs.est.1c02554 PMID:34435767

Engelsman M, Snoek MF, Banks APW, Cantrell P, Wang X, Toms LM, et al. (2019). Exposure to metals and semivolatile organic compounds in Australian fire stations. *Environ Res*. 179(Pt A):108745. doi:10.1016/j.envres.2019.108745 PMID:31546131

Etzel RA, Ashley DL (1994). Volatile organic compounds in the blood of persons in Kuwait during the oil fires. *Int Arch Occup Environ Health*. 66(2):125–9. doi:10.1007/BF00383368 PMID:7806395

Evans DE, Fent KW (2015). Ultrafine and respirable particle exposure during vehicle fire suppression. *Environ Sci Process Impacts*. 17(10):1749–59. doi:10.1039/C5EM00233H PMID:26308547

Fahy R, Evarts B, Stein GP (2021). US fire department profile 2020. National Fire Protection Association. NFPA Research; pp. 1–6. Available from: https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/Emergency-responders/osfdprofile.pdf, accessed June 2022.

Fent KW, Evans DE (2011). Assessing the risk to firefighters from chemical vapors and gases during vehicle fire suppression. *J Environ Monit*. 13(3):536–43. doi:10.1039/c0em00591f PMID:21274476

Fent KW, Evans DE, Babik K, Striley C, Bertke S, Kerber S, et al. (2018). Airborne contaminants during controlled residential fires. *J Occup Environ Hyg*. 15(5):399–412. doi:10.1080/15459624.2018.1445260 PMID:29494297

Fent KW, LaGuardia M, Luellen D, McCormick S, Mayer A, Chen IC, et al. (2020). Flame retardants, dioxins, and furans in air and on firefighters' protective ensembles during controlled residential firefighting. *Environ Int*. 140:105756. doi:10.1016/j.envint.2020.105756 PMID:32388249

Fent KW, Mayer A, Bertke S, Kerber S, Smith D, Horn GP (2019). Understanding airborne contaminants produced by different fuel packages during training fires. *J Occup Environ Hyg*. 16(8):532–43. doi:10.1080/15459624.2019.1617870 PMID:31169466

Ferguson MD, Semmens EO, Weiler E, Domitrovich J, French M, Migliaccio C, et al. (2017). Lung function measures following simulated wildland firefighter exposures. *J Occup Environ Hyg*. 14(9):739–48. doi:10.1080/15459624.2017.1326700 PMID:28609218

Fernando S, Shaw L, Shaw D, Gallea M, VandenEnden L, House R, et al. (2016). Evaluation of firefighter exposure to wood smoke during training exercises at burn houses. *Environ Sci Technol*. 50(3):1536–43. doi:10.1021/acs.est.5b04752 PMID:26726952

Feunekes FD, Jongeneelen FJ, vd Laan H, Schoonhof FH (1997). Uptake of polycyclic aromatic hydrocarbons among trainers in a fire-fighting training facility. *Am Ind Hyg Assoc J*. 58(1):23–8. doi:10.1080/15428119791013035 PMID:9018833

Froines JR, Hinds WC, Duffy RM, Lafuente EJ, Liu WC (1987). Exposure of firefighters to diesel emissions in fire stations. *Am Ind Hyg Assoc J*. 48(3):202–7. doi:10.1080/15298668791384634 PMID:2437785

Gaughan DM, Piacitelli CA, Chen BT, Law BF, Virji MA, Edwards NT, et al. (2014c). Exposures and cross-shift lung function declines in wildland firefighters. *J Occup Environ Hyg*. 11(9):591–603. doi:10.1080/15459624.2014.895372 PMID:24568319

Gill R, Hurley S, Brown R, Tarrant D, Dhaliwal J, Sarala R, et al. (2020). Polybrominated diphenyl ether and organophosphate flame retardants in Canadian fire station dust. *Chemosphere*. 253:126669. doi:10.1016/j.chemosphere.2020.126669 PMID:32464780

Gold A, Burgess WA, Clougherty EV (1978). Exposure of firefighters to toxic air contaminants. *Am Ind Hyg Assoc J*. 39(7):534–9. doi:10.1080/0002889778507805 PMID:211840

Graber JM, Black TM, Shah NN, Caban-Martinez AJ, Lu SE, Brancard T, et al. (2021). Prevalence and predictors of per- and polyfluoroalkyl substances (PFAS) serum levels among members of a suburban US volunteer fire department. *Int J Environ Res Public Health*. 18(7):3730. doi:10.3390/ijerph18073730 PMID:33918459

Hejl AM, Adetona O, Diaz-Sanchez D, Carter JD, Commodore AA, Rathbun SL, et al. (2013). Inflammatory effects of woodsmoke exposure among wildland firefighters working at prescribed burns at the Savannah River Site, SC. *J Occup Environ Hyg*. 10(4):173–80. doi:10.1080/15459624.2012.760064 PMID:23363434

Henn SA, Butler C, Li J, Sussell A, Hale C, Broyles G, et al. (2019). Carbon monoxide exposures among US wildland firefighters by work, fire, and environmental characteristics and conditions. *J Occup Environ Hyg.* 16(12):793–803. doi:10.1080/15459624.2019.1670833 PMID:31658425

Hill TA, Siedle AR, Perry R (1972). Chemical hazards of a fire-fighting training environment. *Am Ind Hyg Assoc J.* 33(6):423–30. doi:10.1080/0002889728506675 PMID:4651528

Hsu JF, Guo HR, Wang HW, Liao CK, Liao PC (2011). An occupational exposure assessment of polychlorinated dibenzo-*p*-dioxin and dibenzofurans in firefighters. *Chemosphere.* 83(10):1353–9. doi:10.1016/j.chemosphere.2011.02.079 PMID:21458022

Hwang J, Taylor R, Cann C, Norris P, Golla V (2019). Evaluation of accumulated polycyclic aromatic hydrocarbons and asbestiform fibers on firefighter vehicles: pilot study. *Fire Technol.* 55(6):2195–213. doi:10.1007/s10694-019-00851-7

Jankovic J, Jones W, Burkhart J, Noonan G (1991). Environmental study of firefighters. *Ann Occup Hyg.* 35(6):581–602. doi:10.1093/annhyg/35.6.581 PMID:1768008

Jayatilaka NK, Restrepo P, Davis Z, Vidal M, Calafat AM, Ospina M (2019). Quantification of 16 urinary biomarkers of exposure to flame retardants, plasticizers, and organophosphate insecticides for biomonitoring studies. *Chemosphere.* 235:481–91. doi:10.1016/j.chemosphere.2019.06.181 PMID:31272008

Jayatilaka NK, Restrepo P, Williams L, Ospina M, Valentin-Blasini L, Calafat AM (2017). Quantification of three chlorinated dialkyl phosphates, diphenyl phosphate, 2,3,4,5-tetrabromobenzoic acid, and four other organophosphates in human urine by solid phase extraction-high performance liquid chromatography-tandem mass spectrometry. *Anal Bioanal Chem.* 409(5):1323–32. doi:10.1007/s00216-016-0061-4 PMID:27838756

Jin C, Sun Y, Islam A, Qian Y, Ducatman A (2011). Perfluoroalkyl acids including perfluorooctane sulfonate and perfluorohexane sulfonate in firefighters. *J Occup Environ Med.* 53(3):324–8. doi:10.1097/JOM.0b013e31820d1314 PMID:21346631

Kato K, Kalathil AA, Patel AM, Ye X, Calafat AM (2018). Per- and polyfluoroalkyl substances and fluorinated alternatives in urine and serum by on-line solid phase extraction-liquid chromatography-tandem mass spectrometry. *Chemosphere.* 209:338–45. doi:10.1016/j.chemosphere.2018.06.085 PMID:29935462

Keir JLA, Akhtar US, Matschke DMJ, White PA, Kirkham TL, Chan HM, et al. (2020). Polycyclic aromatic hydrocarbon (PAH) and metal contamination of air and surfaces exposed to combustion emissions during emergency fire suppression: implications for firefighters' exposures. *Sci Total Environ.* 698:134211. doi:10.1016/j.scitotenv.2019.134211 PMID:31514022

Khalil N, Ducatman AM, Sinari S, Billheimer D, Hu C, Littau S, et al. (2020). Per- and polyfluoroalkyl substance and cardio metabolic markers in firefighters. *J Occup Environ Med.* 62(12):1076–81. doi:10.1097/JOM.0000000000002062 PMID:33105404

Kirk KM, Logan MB (2015). Firefighting instructors' exposures to polycyclic aromatic hydrocarbons during live fire training scenarios. *J Occup Environ Hyg.* 12(4):227–34. doi:10.1080/15459624.2014.955184 PMID:25679824

Kirk KM, Logan MB (2019). Exposures to air contaminants in compartment fire behavior training (CFBT) using particleboard fuel. *J Occup Environ Hyg.* 16(7):432–9. doi:10.1080/15459624.2019.1603388 PMID:31021707

Kirkham TL, Koehoorn MW, Davies H, Demers PA (2011). Characterization of noise and carbon monoxide exposures among professional firefighters in British Columbia. *Ann Occup Hyg.* 55(7):764–74. doi:10.1093/annhyg/mer038 PMID:21765005

Laitinen J, Mäkelä M, Mikkola J, Huttu I (2010). Fire fighting trainers' exposure to carcinogenic agents in smoke diving simulators. *Toxicol Lett.* 192(1):61–5. doi:10.1016/j.toxlet.2009.06.864 PMID:19576276

Laitinen J, Mäkelä M, Mikkola J, Huttu I (2012). Firefighters' multiple exposure assessments in practice. *Toxicol Lett.* 213(1):129–33. doi:10.1016/j.toxlet.2012.06.005 PMID:22710199

Laitinen JA, Koponen J, Koikkalainen J, Kiviranta H (2014). Firefighters' exposure to perfluoroalkyl acids and 2-butoxyethanol present in firefighting foams. *Toxicol Lett.* 231(2):227–32. doi:10.1016/j.toxlet.2014.09.007 PMID:25447453

Lam D (2009). [Female firefighters are "equal to men"]. Diário de Notícias. 1 June 2009. Available from: https://www.dn.pt/portugal/sul/bombeiras-sao-iguais-aos-homens-1250127.html, accessed 13 June 2022. [Portuguese]

Leary DB, Takazawa M, Kannan K, Khalil N (2020). Perfluoroalkyl substances and metabolic syndrome in firefighters: a pilot study. *J Occup Environ Med.* 62(1):52–7. doi:10.1097/JOM.0000000000001756 PMID:31658221

Lowry WT, Juarez L, Petty CS, Roberts B (1985). Studies of toxic gas production during actual structural fires in the Dallas area. *J Forensic Sci.* 30(1):59–72. doi:10.1520/JFS10965J PMID:3981122

MacSween K, Paton-Walsh C, Roulston C, Gurette EA, Edwards G, Reisen F, et al. (2020). Cumulative firefighter exposure to multiple toxins emitted during prescribed burns in Australia. *Expo Health.* 12(4):721–33. doi:10.1007/s12403-019-00332-w

Markowitz JS, Gutterman EM, Schwartz S, Link B, Gorman SM (1989). Acute health effects among firefighters exposed to a polyvinyl chloride (PVC) fire. *Am J*

Epidemiol. 129(5):1023–31. doi:10.1093/oxfordjournals.aje.a115206 PMID:2705423

Markowitz SB, Garibaldi K, Lilis R, Landrigan PJ (1991). Asbestos exposure and fire fighting. *Ann N Y Acad Sci*. 643:573–7. doi:10.1111/j.1749-6632.1991.tb24507.x PMID:1809170

Materna BL, Jones JR, Sutton PM, Rothman N, Harrison RJ (1992). Occupational exposures in California wildland fire fighting. *Am Ind Hyg Assoc J*. 53(1):69–76. doi:10.1080/15298669291359311 PMID:1317093

Mayer AC, Fent KW, Bertke S, Horn GP, Smith DL, Kerber S, et al. (2019). Firefighter hood contamination: efficiency of laundering to remove PAHs and FRs. *J Occup Environ Hyg*. 16(2):129–40. doi:10.1080/15459624.2018.1540877 PMID:30427284

Mayer AC, Fent KW, Chen IC, Sammons D, Toennis C, Robertson S, et al. (2021). Characterizing exposures to flame retardants, dioxins, and furans among firefighters responding to controlled residential fires. *Int J Hyg Environ Health*. 236(2021):113782. doi:10.1016/j.ijheh.2021.113782 PMID:34119852

McMahon CK, Bush PB (1992). Forest worker exposure to airborne herbicide residues in smoke from prescribed fires in the southern United States. *Am Ind Hyg Assoc J*. 53(4):265–72. doi:10.1080/15298669291359636 PMID:1529920

McNamara ML, Semmens EO, Gaskill S, Palmer C, Noonan CW, Ward TJ (2012). Base camp personnel exposure to particulate matter during wildland fire suppression activities. *J Occup Environ Hyg*. 9(3):149–56. doi:10.1080/15459624.2011.652934 PMID:22364357

Minty BD, Royston D, Jones JG, Smith DJ, Searing CS, Beeley M (1985). Changes in permeability of the alveolar-capillary barrier in firefighters. *Br J Ind Med*. 42(9):631–4. doi:10.1136/oem.42.9.631 PMID:3899161

Miranda AI, Martins V, Cascão P, Amorim JH, Valente J, Borrego C, et al. (2012). Wildland smoke exposure values and exhaled breath indicators in firefighters. *J Toxicol Environ Health A*. 75(13–15):831–43. doi:10.1080/15287394.2012.690686 PMID:22788370

Miranda AI, Martins V, Cascão P, Amorim JH, Valente J, Tavares Ra (2011). [Air quality and firefighter's exposure to experimental forest fires' smoke.] *Silva Lusitana*. 19:23–40. [Portuguese]

Miranda AI, Martins V, Cascão P, Amorim JH, Valente J, Tavares R, et al. (2010). Monitoring of firefighters exposure to smoke during fire experiments in Portugal. *Environ Int*. 36(7):736–45. doi:10.1016/j.envint.2010.05.009 PMID:20579737

Musk AW, Smith TJ, Peters JM, McLaughlin E (1979). Pulmonary function in firefighters: acute changes in ventilatory capacity and their correlates. *Br J Ind Med*. 36(1):29–34. doi:10.1136/oem.36.1.29 PMID:444439

Naeher LP, Achtemeier GL, Glitzenstein JS, Streng DR, Macintosh D (2006). Real-time and time-integrated $PM_{2.5}$ and CO from prescribed burns in chipped and non-chipped plots: firefighter and community exposure and health implications. *J Expo Sci Environ Epidemiol*. 16(4):351–61. doi:10.1038/sj.jes.7500497 PMID:16736059

Naeher LP, Barr DB, Adetona O, Simpson CD (2013). Urinary levoglucosan as a biomarker for woodsmoke exposure in wildland firefighters. *Int J Occup Environ Health*. 19(4):304–10. doi:10.1179/2049396713Y.0000000037 PMID:24588036

Navarro KM, Cisneros R, Noth EM, Balmes JR, Hammond SK (2017). Occupational exposure to polycyclic aromatic hydrocarbon of wildland firefighters at prescribed and wildland fires. *Environ Sci Technol*. 51(11):6461–9. doi:10.1021/acs.est.7b00950 PMID:28498656

Navarro KM, Cisneros R, Schweizer D, Chowdhary P, Noth EM, Balmes JR, et al. (2019). Incident command post exposure to polycyclic aromatic hydrocarbons and particulate matter during a wildfire. *J Occup Environ Hyg*. 16(11):735–44. doi:10.1080/15459624.2019.1657579 PMID:31545144

Navarro KM, West MR, O'Dell K, Sen P, Chen IC, Fischer EV, et al. (2021). Exposure to particulate matter and estimation of volatile organic compounds across wildland firefighter job tasks. *Environ Sci Technol*. 55(17):11795–804. doi:10.1021/acs.est.1c00847 PMID:34488352

Neitzel R, Naeher LP, Paulsen M, Dunn K, Stock A, Simpson CD (2009). Biological monitoring of smoke exposure among wildland firefighters: a pilot study comparing urinary methoxyphenols with personal exposures to carbon monoxide, particular matter, and levoglucosan. *J Expo Sci Environ Epidemiol*. 19(4):349–58. doi:10.1038/jes.2008.21 PMID:18446186

NIOSH (1991). Health Hazard Evaluation Report No. HETA 91-312-2185. Firefighter's exposure to smoke during fire suppression activities at wildland fires. Prepared by Kelly J. Cincinnati (OH), USA: National Institute for Occupational Safety and Health. Available from: https://www.cdc.gov/niosh/hhe/reports/pdfs/1991-0312-2185.pdf, accessed June 2022.

NIOSH (1992a). Health Hazard Evaluation Report No. HETA 92-045-2260. Characterization of fire fighters' exposures to chemical contaminants during fire suppression operations. Prepared by Kelly J. Cincinnati (OH), USA: National Institute for Occupational Safety and Health. Available from: http://www.cdc.gov/niosh/hhe/reports/pdfs/1992-0045-2260.pdf, accessed 30 August 2022.

NIOSH (1992b). Health Hazard Evaluation Report No. HETA 88-320-2176. US Department of the Interior, National Park Service, Yellowstone National Park, Wyoming. Prepared by Reh CM, Deitchman SD. Cincinnati (OH), USA: National Institute for Occupational Safety and Health. Available from: https://www.cdc.gov/niosh/hhe/reports/pdfs/1988-0320-2176.pdf.

NIOSH (1994). Health Hazard Evaluation Report No. HETA 90-0365-2415. US Department of the Interior, National Park Service, Yosemite National Park, California. Prepared by Reh CM, Letts D, Deitchman S. Cincinnati (OH), USA: National Institute of Occupational Safety and Health. Available from: https://www.cdc.gov/niosh/hhe/reports/pdfs/1990-0365-2415.pdf, accessed 15 May 2023.

NIOSH (1998). Health Hazard Evaluation Report No. HETA 96-0171-2692. Bureau of Alcohol, Tobacco, and Firearms. Washington, DC. Prepared by Kinnes GM, Hine GA. Cincinnati (OH), USA: National Institute for Occupational Safety and Health. Available from: https://www.cdc.gov/niosh/hhe/reports/pdfs/1996-0171-2692.pdf, accessed 15 May 2023.

NIOSH (2016). Health Hazard Evaluation Report No. HETA 2015-0159-3265. Evaluation of diesel exhaust exposures at multiple fire stations in a city fire department. Prepared by Couch J, Broadwater K, de Perio MA. Cincinnati (OH), USA: National Institute for Occupational Safety and Health. Available from: https://www.cdc.gov/niosh/hhe/reports/pdfs/2015-0159-3265.pdf, accessed 30 August 2022.

NIOSH (2019). Health Hazard Evaluation Report No. 2017-0076-3352. Evaluation of wildland fire fighters' exposures to asbestos during a prescribed burn. Prepared by Grant MP. Cincinnati (OH), USA: National Institute for Occupational Safety and Health. Available from: https://www.cdc.gov/niosh/hhe/reports/pdfs/2017-0076-3352.pdf, accessed 30 August 2022.

Park JS, Voss RW, McNeel S, Wu N, Guo T, Wang Y, et al. (2015). High exposure of California firefighters to polybrominated diphenyl ethers. *Environ Sci Technol*. 49(5):2948–58. doi:10.1021/es5055918 PMID:25643236

Peaslee GF, Wilkinson JT, McGuinness SR, Tighe M, Caterisano N, Lee S, et al. (2020). Another pathway for firefighter exposure to per- and polyfluoroalkyl substances: firefighter textiles. *Environ Sci Technol Lett*. 7(8):594–9. doi:10.1021/acs.estlett.0c00410

Pośniak M (2000). [Chemical hazards in fire-fighting environments]. *Med Pr*. 51(4):335–44.[Polish] PMID: 11059406

Poutasse CM, Poston WSC, Jahnke SA, Haddock CK, Tidwell LG, Hoffman PD, et al. (2020). Discovery of firefighter chemical exposures using military-style silicone dog tags. *Environ Int*. 142:105818. doi:10.1016/j.envint.2020.105818 PMID:32521346

Reinhardt T, Ottmar R (2000). Smoke exposure at western wildfires. Portland (OR), USA: United States Department of Agriculture, Pacific Northwest Research Station. doi:10.2737/PNW-RP-525

Reinhardt TE, Broyles G (2019). Factors affecting smoke and crystalline silica exposure among wildland firefighters. *J Occup Environ Hyg*. 16(2):151–64. doi:10.1080/15459624.2018.1540873 PMID:30407130

Reinhardt TE, Ottmar RD (2004). Baseline measurements of smoke exposure among wildland firefighters. *J Occup Environ Hyg*. 1(9):593–606. doi:10.1080/15459620490490101 PMID:15559331

Reisen F, Brown S, Cheng M (2006). Air toxics in bushfire smoke: firefighter's exposure during prescribed burns. In: Viegas DX, editor. 5th International Conference on Forest Fire Research, November 2006, Coimbra, Portugal.

Reisen F, Brown SK (2009). Australian firefighters' exposure to air toxics during bushfire burns of autumn 2005 and 2006. *Environ Int*. 35(2):342–52. doi:10.1016/j.envint.2008.08.011 PMID:18829114

Reisen F, Hansen D, Meyer CP (2011). Exposure to bushfire smoke during prescribed burns and wildfires: firefighters' exposure risks and options. *Environ Int*. 37(2):314–21. doi:10.1016/j.envint.2010.09.005 PMID:20956017

Robinson MS, Anthony TR, Littau SR, Herckes P, Nelson X, Poplin GS, et al. (2008). Occupational PAH exposures during prescribed pile burns. *Ann Occup Hyg*. 52(6):497–508. doi:10.1093/annhyg/men027 PMID:18515848

Rom WN, Weiden M, Garcia R, Yie TA, Vathesatogkit P, Tse DB, et al. (2002). Acute eosinophilic pneumonia in a New York City firefighter exposed to World Trade Center dust. *Am J Respir Crit Care Med*. 166(6):797–800. doi:10.1164/rccm.200206-576OC PMID:12231487

Rotander A, Kärrman A, Toms LM, Kay M, Mueller JF, Gómez Ramos MJ (2015a). Novel fluorinated surfactants tentatively identified in firefighters using liquid chromatography quadrupole time-of-flight tandem mass spectrometry and a case-control approach. *Environ Sci Technol*. 49(4):2434–42. doi:10.1021/es503653n PMID:25611076

Rotander A, Toms L-ML, Aylward L, Kay M, Mueller JF (2015b). Elevated levels of PFOS and PFHxS in firefighters exposed to aqueous film forming foam (AFFF). *Environ Int*. 82:28–34. doi:10.1016/j.envint.2015.05.005 PMID:26001497

Ruokojärvi P, Aatamila M, Ruuskanen J (2000). Toxic chlorinated and polyaromatic hydrocarbons in simulated house fires. *Chemosphere*. 41(6):825–8. doi:10.1016/S0045-6535(99)00549-4 PMID:10864154

Salama KF, Bashawri LA (2017). Biochemical and hematological changes among Saudi firefighters in the eastern province. *Int J Environ Health Eng*. 6(1):2. doi:10.4103/ijehe.ijehe_12_15

Sebastião R, Sorte S, Fernandes JM, Miranda AI (2021). Classification of critical levels of CO exposure of firefighters through monitored heart rate. *Sensors (Basel)*. 21(5):1561. doi:10.3390/s21051561 PMID:33668116

Shaw SD, Berger ML, Harris JH, Yun SH, Wu Q, Liao C, et al. (2013). Persistent organic pollutants including polychlorinated and polybrominated dibenzo-*p*-dioxins and dibenzofurans in firefighters from Northern

California. *Chemosphere*. 91(10):1386–94. doi:10.1016/j.chemosphere.2012.12.070 PMID:23395527

Shen B, Whitehead TP, Gill R, Dhaliwal J, Brown FR, Petreas M, et al. (2018). Organophosphate flame retardants in dust collected from United States fire stations. *Environ Int*. 112:41–8. doi:10.1016/j.envint.2017.12.009 PMID:29247842

Shen B, Whitehead TP, McNeel S, Brown FR, Dhaliwal J, Das R, et al. (2015). High levels of polybrominated diphenyl ethers in vacuum cleaner dust from California fire stations. *Environ Sci Technol*. 49(8):4988–94. doi:10.1021/es505463g PMID:25798547

Sjöström M, Juander A, Strandberg B, Lewné M, Bigert C (2019). Airborne and dermal exposure to polycyclic aromatic hydrocarbons, volatile organic compounds, and particles among firefighters and police investigators. *Ann Work Expo Health*. 63(5):533–45. doi:10.1093/annweh/wxz030 PMID:31111145

Slaughter JC, Koenig JQ, Reinhardt TE (2004). Association between lung function and exposure to smoke among firefighters at prescribed burns. *J Occup Environ Hyg*. 1(1):45–9. doi:10.1080/15459620490264490 PMID:15202156

Smith WR, Montopoli G, Byerly A, Montopoli M, Harlow H, Wheeler AR 3rd (2013). Mercury toxicity in wildland firefighters. *Wilderness Environ Med*. 24(2):141–5. doi:10.1016/j.wem.2013.01.004 PMID:23453729

Strandberg B, Julander A, Sjöström M, Lewné M, Koca Akdeva H, Bigert C (2018). Evaluation of polyurethane foam passive air sampler (PUF) as a tool for occupational PAH measurements. *Chemosphere*. 190:35–42. doi:10.1016/j.chemosphere.2017.09.106 PMID:28985535

Swiston JR, Davidson W, Attridge S, Li GT, Brauer M, van Eeden SF (2008). Wood smoke exposure induces a pulmonary and systemic inflammatory response in firefighters. *Eur Respir J*. 32(1):129–38. doi:10.1183/09031936.00097707 PMID:18256060

Trowbridge J, Gerona RR, Lin T, Rudel RA, Bessonneau V, Buren H, et al. (2020). Exposure to perfluoroalkyl substances in a cohort of women firefighters and office workers in San Francisco. *Environ Sci Technol*. 54(6):3363–74. doi:10.1021/acs.est.9b05490 PMID:32100527

UK Home Office (2021a). Official statistics. Fire and rescue workforce and pensions statistics: England, April 2020 to March 2021. London, England: United Kingdom Home Office. Available from: https://www.gov.uk/government/statistics/fire-and-rescue-workforce-and-pensions-statistics-england-april-2020-to-march-2021/fire-and-rescue-workforce-and-pensions-statistics-england-april-2020-to-march-2021, accessed February 2023.

Wu CM, Song CC, Chartier R, Kremer J, Naeher L, Adetona O (2021). Characterization of occupational smoke exposure among wildland firefighters in the midwestern United States. *Environ Res*. 193:110541. doi:10.1016/j.envres.2020.110541 PMID:33249041

Young AS, Sparer-Fine EH, Pickard HM, Sunderland EM, Peaslee GF, Allen JG (2021). Per- and polyfluoroalkyl substances (PFAS) and total fluorine in fire station dust. *J Expo Sci Environ Epidemiol*. 31(5):930–42. doi:10.1038/s41370-021-00288-7 PMID:33542478