ORIGINAL ARTICLE

The risk to the United Kingdom population of zinc cadmium sulfide dispersion by the Ministry of Defence during the "cold war"

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Objectives: To estimate exposures to cadmium (Cd) received by the United Kingdom population as a result of the dispersion of zinc Cd sulfide (ZnCdS) by the Ministry of Defence between 1953 and 1964, as a simulator of biological warfare agents.

Methods: A retrospective risk assessment study was carried out on the United Kingdom population during the period 1953–64. This determined land and air dispersion of ZnCdS over most of the United Kingdom, inhalation exposure of the United Kingdom population, soil contamination, and risks to personnel operating equipment that dispersed ZnCdS.

Results: About 4600 kg ZnCdS were dispersed from aircraft and ships, at times when the prevailing winds would allow large areas of the country to be covered. Cadmium released from 44 long range trials for which data are available, and extrapolated to a total of 76 trials to allow for trials with incomplete information, is about 1.2% of the estimated total release of Cd into the atmosphere over the same period. "Worst case" estimates are 10 µg Cd inhaled over 8 years, equivalent to Cd inhaled in an urban environment in 12–100 days, or from smoking 100 cigarettes. A further 250 kg ZnCdS was dispersed from the land based sites, but significant soil contamination occurred only in limited areas, which were and have remained uninhabited. Of the four personnel involved in the dispersion procedures (who were probably exposed to much higher concentrations of Cd than people on the ground), none are suspected of having related illnesses.

Conclusion: Exposure to Cd from dissemination of ZnCdS during the "cold war" should not have resulted in adverse health effects in the United Kingdom population.

Early in the "cold war", from 1953 to 1964, a programme of zinc cadmium sulfide (ZnCdS) dispersion tests was conducted by the British Ministry of Defence, to simulate biological attack by communist forces. Discrete dissemination of toxic biological agents over the entire country was considered a high risk for an island such as Britain. Studies were conducted in Britain, America, and Scandinavia to determine whether small particles could be widely dispersed from aircraft or vehicles. Zinc cadmium sulfide was a suitable tracer, because it fluoresces under ultraviolet (UV) light and single particles could be counted on samplers around the country.

Initially various static disseminating and recording devices were tested at ground level, followed by release from vehicles and aircraft, from which the primary threat existed. Further studies investigated release from ships in the English Channel and the Irish Sea.

When information about the trials was released in the 1990s, public concern about health risks was voiced in America and Britain, but a toxicological assessment of the dispersion tests of ZnCdS carried out by the United States Army was reassuring.[1] We independently reviewed the United Kingdom trials, assessing possible human exposure to cadmium (Cd) (the presumed toxic component of ZnCdS),[1] and conducted a risk assessment in comparison with other sources of Cd.

METHODS

Field trial programmes, reports, and technical papers from Porton Down[2–36 37] detailing the United Kingdom trials (most of which are, or shortly will be, available through the Public Records Office) were provided by the Defence Evaluation and Research Agency. Planned field programmes, operation dates, dissemination routes, quantities of ZnCdS disseminated and recovered and locations of sampling stations were described. Two internal reviews were conducted.[38 39] Ground disseminating trials each released 0.4–9 kg ZnCdS from either a point source, to test equipment, or a vehicle, to simulate stealth attack. In early programmes fallout was measured in Petri dishes placed at about 2 m intervals in a grid around the disseminator.

Not all disseminations from aircraft and ships were comprehensively recorded. Some are reported more than once, and for others (approved in field programmes) no details are available. The aircraft trials over the sea were conducted 10–50 miles off the coast at an altitude of about 300 m. Particle fallout was monitored by cascade impactors or drum impactors located across the country. Widespread dissemination over hundreds of miles occurred.

The first trial using aircraft dissemination in 1956 released 12 kg ZnCdS over Porton from a hand fed Venturi unit below the aircraft. The last recorded aircraft dissemination in 1963 released 68 kg ZnCdS over 62 miles upwind and south west of Norwich. Other programmes, dated 1960–4, proposed dissemination by air at an unstated location (programme 23/60) and over Cardington (programmes 2/61, 24/62 and 10/63), Netheravon (programme 14/63) and Norwich (programme 2/64), but no details are available. Nine disseminations from ships are recorded in October and November 1959 and January 1963.

Abbreviations: UV, ultraviolet; Cd, cadmium; ZnCdS, zinc cadmium sulfide

Table 1 Land based dissemination of ZnCdS by the United Kingdom Ministry of Defence sampled by fallout impactors at near distance (<300 m) and cascade impactors at 25 and 50 miles

Field report FR	Material disseminated (g)	Material recovered from disseminator (g)	Location	Additional Cd load to soil (μg Cd/g soil DM, or related to FR 370)	Area above legal maximum concentration*
Programme 1/54: assessment of fallout of fluorescent powder emitted from the Stanford type aerosol generator:					
353	367	302	RAF Beaulieu airfield (Hampshire)	2.5 (180†)	10×2.5 (138×25†) m
405§	1) 736	5	RAF Beaulieu airfield	0.1	None
	2) 489	110		1.6	None
Programme 17/53: long distance travel of particulate clouds:					
370	3462	507	RAF Beaulieu airfield	3.3	4×2 m
371	2291	1032	RAF Beaulieu airfield	54% and 27% of emissions in FR No 370 at 40 and 80 km from source	Probably none
372	3106	409	Porton	46% of emissions in FR 370	Probably none
373	3031	343	RAF Yatesbury	40% of emissions in FR 370	Probably none
382	2227	709	A35, A351 and B3075 near Blandford, Salisbury‡	56% and 39% of in FR 370 at 40 and 80 km from source	Probably none
388	2959	355	RAF Hullavington, Nr Chippenham	ZnCdS cloud missed samplers	Probably none
392	2345	337	4 Miles of minor roads near Frome, Somerset	30% and 15% of emissions in FR 370 at 40 and 80 km from source	Probably none

*Assuming critical addition is about 85 μg/cm^2, which is roughly equal to +2.3 mg/kg soil DM, assuming baseline soil concentration is 0.7 mg/kgDM.
†There is confusion in the report over units. The higher values refer to the unlikely assumption that the units are μg/Petri dish, rather than mg/m^2.
‡Dispersion over distance from vehicle.
§Comparison between two disseminators.

For the long range trials, total ZnCdS disseminated was estimated from dissemination rate and trial duration. The theoretical inhaled dose at the sampling point with maximum particle count (the dose received by a person at that point during the passage of the particle cloud) was calculated from the number of inhaled particles. The following assumptions were made: the breathing rate of an active adult is 16.6 l/min,[1] the number of particles/g is1.7×10^{10},[11 20] there was a 50% loss of fluorescence in particles due to exposure to sunlight,[38] and the ZnCdS was prepared from 60% ZnS and 40% CdS (31% Cd).[38]

RESULTS

About 51 trials were conducted from ground based sources, mostly at Porton and local airfields, with an estimated total of 250 kg ZnCdS disseminated (table 1). Calculations of maximum fallout are based on 20 000 μg/petri dish (90 mm diameter), the highest concentration reliably recorded.[40] This concentration was found only in one trial[1] and equates to 110 μg/cm^2.

A total of 42 trials with dissemination by air are documented, of which 29 took place over land, 11 over the sea, and two over both land and sea (table 2). The amount of ZnCdS disseminated could be calculated for 35 of the 42 trials, with a mean of 70 kg, range 5–139 kg, and a total amount disseminated in 35 trials of 2446 kg.

The highest particle count (4315) was found at Dorchester after dissemination over the English Channel in 1959, with 127 kg ZnCdS released from a Venturi operated dispenser mounted in a Valetta aircraft, with the flight path finishing close inshore just south of Swanage. Counts over 1000 were also recorded over Cardington in August 1957 (particle count =3403) and November 1957 (1070), and at Silloth (1591), the start of a flight path over northern England and the North Sea.

There were nine trials with dissemination from ships (table 3). The highest particle count (1676) was recorded at Dorchester when 11 kg ZnCdS was discharged 18 miles south of Portland Bill. The second set of trials, conducted in the English Channel in January 1963, concerned the penetration of ships by aerosol, and no land based monitoring was conducted. In total 250 kg ZnCdS was released from nine trials.

An estimated 2700 kg was released from 35 air disseminated and nine ship disseminated trials, and 250 kg from land based trials. Assuming that the mean of 70 kg was released from each of the seven undocumented long range trials, an estimated 3450 kg was disseminated in total. The programmes dated 1960–4, for which further data are not available, are summarised in table 4. Altogether 28 trials were proposed, but three were small and are not considered further. Proposed release of ZnCdS in the remaining 25 trials was 1387 kg. Assuming these trials took place, this would have resulted in a total ZnCdS disseminated during 8 years of about 4850 kg (1503 kg Cd).

The largest estimated dose received by any person during any one trial was 0.42 μg ZnCdS (0.13 μg Cd) (table 2). Assuming a total of 76 long range dissemination trials (51 trials in tables 2 and 3 and 25 trials in table 4), and a "worst case" assumption that at each trial a person received the maximum dose (0.13 μg Cd, calculated from the Dorchester measurements), then the maximum total dose over an 8 year period was about 10 μg Cd.

DISCUSSION

Zinc cadmium sulfide is a sintered, crystalline compound the photosensitivity of which makes it useful for photography, and it is thought to be safe in this role.[41] However, Cd accumulates in the body, especially in the kidneys and to a lesser extent in the liver. There is uncertainty about the fate of ZnCdS when it is breathed deep into the lungs. Cadmium ions are carcinogenic in the alveolar cells, but the insolubility of ZnCdS probably reduces this potential. About 5% of ingested Cd[42] and up to 57% of inhaled Cd[43] is absorbed, bound to albumen or to metallothionein. Initially stored in the liver, Cd metallothionein enters the kidneys, where the lysosomes in the proximal tubules release the Cd, impairing tubule function. The estimated 1.5 tonnes total Cd dissemination by the Ministry of Defence compares with an estimated 15 tonnes Cd released into the atmosphere from United Kingdom industry annually.[44] Thus, the United Kingdom trials increased the atmospheric Cd load by about 1.2%.

The estimated maximum inhaled dose from any one trial was 0.13 μg Cd, which is several orders of magnitude lower than the Cd concentration in air (100 μg Cd/l) required to cause lung damage in mammals.[45] Our "worst case" estimate of cumulative personal dose received from all trials was about 10 μg, which is of the same order as the estimated total Cd inhalation in North American cities affected by the tests (24.4, 14.5, and 6.8 μg in St Louis, Winnipeg, and Minneapolis, respectively).[1]

Table 2 Trials of dissemination from aircraft, and estimated theoretical inhaled dose of ZnCdS at the sampling point with maximum particle count

Report	Date of trial	Approximate amount released (kg)	Location	Maximum particle count	Sampling rate (l/min)	Estimated inhaled dose (μg)*
FR 504	11 September 1956	12	Porton	351	17.5†	0.039
	17 September 1956	111	North Sea	93	17.5	0.010
FR 514	25 April 1957	138	North Sea	337	22	0.030
FR 516	28 August 1957	5	Cardington	3403	20	0.332
FR 515	13 November 1957	117	North Sea	112	10	0.022
PTP 633	14 November 1957	**	Cardington	99¶	20	0.010
	15 November 1957	**	Cardington	1070¶	20	0.104
PN 68	22 July 1958	98	Irish Sea	415	20	0.041
PN 138	18/19 September 1958	116	English Channel	674	20.5	0.064
PN 139	28 October 1958	120	English Channel	669	20.5	0.064
PN 145	11 December 1958	83	North Sea	144	20.5	0.014
PN 185	14 April 1959	123	English Channel	182	20.5	0.017
PN 186	26 May 1959	139	North Sea and NE England	1591	21.5	0.145
PN 187	7 July 1959	139	English Channel & Cornwall	123	20	0.012
PN 188	18 August 1959	127	English Channel	4315	20	0.421
PN 253	19 March 1958	**	Cardington	**	**	
	4 March 1959	**	Cardington	**	**	
	7 May 1959	**	Cardington	**	**	
	9 September 1960	**	Cardington	**	**	
PN 134	29 May 1959	45	Cardington	96¶	20	0.009
	3 June 1959	45	Cardington	44¶	20	0.004
	25 August 1959	45	Cardington	17¶	20	0.002
	15 September 1959	45	Cardington	129¶	20	0.013
	16 September 1959	45	Cardington	34¶	20	0.003
	17 September 1959	45	Cardington	‡	20	
	18 September 1959	45	Cardington	‡	20	
	22 September 1959	45	Cardington	8¶	20	0.001
	23 September 1959 (1st)	45	Cardington	278¶	20	0.027
	23 September 1959 (2nd)	45	Cardington	271¶	20	0.026
PN 183	21 April 1960	17.5	Cardington	209¶	20	0.020
	25 May 1960	17.5	Cardington	143¶	20	0.014
	26 May 1960 (1st)	17.5	Cardington	285¶	20	0.028
	26 May 1960 (2nd)	17.5	Cardington	315¶	20	0.031
	26 May 1960 (3rd)	17.5	Cardington	157¶	20	0.015
	17 June 1960	91	Cardington	387	20	0.038
	29 June 1960	91	Cardington	30	20	0.003
	30 June 1960	91	Cardington	87	20	0.008
	1 July 1960	91	Cardington	36	20	0.004
PTP 764	27 October 1960	74	English Channel	2§	21.3	0.000
	28 October 1960	74	English Channel	91§	19.8	0.009
Programme 17/60/PFTR 610††	**	**	Salisbury	**	**	
PFTR 610††	28 March 1963	68	Norwich	377	10	0.074

Several additional programmes were approved, but details of these trials are unavailable. These include proposed aircraft dissemination trials with unspecified location (programme 23/60), at Cardington (programme 2/61, 24/62 and 10/63), Netheravon (programme 14/63) and over Norwich (programme 2/64).
*Assuming respiratory rate of 16.6 l/min[1], 1.7×0^{10} particles/g (FR 504; PN 185), and loss of 50% of fluorescence (Collins 1981) . Thus, for the trial on 18 August 1959, the inhaled dose at Dorchester is estimated as (4315 (particle count)×2 (loss of fluorescence)×16.6 (breathing rate))/(20 (sampling rate)×1.7×10^{10} (number of particles/g)) = 4.21×10^{-7} g=0.42 μg (0.13 μg Cd).
†Assumed flow rate.
‡Pages 18 and 19 of PN 134 missing.
§Land based sampling (samples were also collected at sea).
¶At height 2 m.
**Not given.
††PFTR 610 missing, but details are reported elsewhere[39].
FR=field report; PN=Porton note; PTP=Porton technical paper; PFTR=Porton field trial report.

The National Research Council estimated that the average yearly inhalation dose of Cd from other sources was 30–250 μg, with smoking adding 2–4 μg/20 cigarettes.[1] Thus, the "worst case" dose in the United Kingdom equated to the amount of Cd inhaled in an urban environment in 12–100 days, or from smoking about 100 cigarettes.

Being insoluble, CdS has a lower bioavailability when inhaled than soluble Cd compounds.[46] However, the possibility of photodegradation of a proportion of the ZnCdS to soluble forms—such as $ZnCdSO_4$—cannot be ruled out. Assuming renal accumulation of 35% of Cd cleared by the lungs, and lung clearance of 56% of inhaled Cd,[46] a 10 μg inhaled dose could result in an additional renal burden of about 2 μg Cd. As the currently accepted critical limit of Cd in the renal cortex is 200 μg/g,[47] any additional renal burden was negligible.

The immediate contamination from ground based dissemination was probably not a serious problem as most releases were on airfields, which were not used for food production. There are two perceived risks of long term soil contamination, to garden plants subsequently grown on the site which may accumulate and contaminate consumers, and to children consuming contaminated soil. No long term adverse effects through garden plants have been established from Cd contaminated garden soil at Shipham.[48]

United Kingdom regulations for sewage sludge application provide guidance on safe Cd concentrations in soils.[49] Up to 3 μg Cd/g soil dry matter in the top 20 cm is permitted, with a maximum deposition of 1.5 μg Cd/cm^2/10 years. The deposition rate of 110 μg/cm^2 at Beaulieu exceeds this limit, but is not illegal as it does not arise from sewage. Assuming a soil bulk

Table 3 Trials of dissemination from ships, and estimated theoretical inhaled dose of ZnCdS at the land based sampling point with maximum particle count

Report	Date of trial	Approximate amount released (kg)	Location	Maximum particle count	Sampling rate (l/min)	Estimated inhaled dose (μg)*
PN 146/203	7 October 1959	11	English Channel	1676	20.4	0.160
	7/8 November 1959	93	English Channel	40	20.2	0.004
	9/10 November 1959	95	Irish Sea	115	21.4	0.010
PTP 893	28 January 1963	7.6	English Channel	†		
	28 January 1963	8.6	English Channel	†		
	29 January 1963	9.5	English Channel	†		
	29 January 1963	4.8	English Channel	†		
	30 January 1963	10.2	English Channel	†		
	30 January 1963	10.4	English Channel	†		

*Assuming respiratory rate of 16.6 l/min (NRC 1997), 1.7×10^{10} particles/g (FR 504; PN 185) and loss of 50% of fluorescence.[38]
†Land based sampling not done.
PN Porton note; PTP Porton technical paper.

density of 1.5 g/cm^3, the top 20 cm of soil contains at most an additional 3.3 μg Cd/g dry matter from the Beaulieu test. Added to the median Cd soil concentration (0.7 μg/g), the expected maximum is 4 μg/g dry matter, above the permitted maximum for sewage sludge application, although the area affected was small (table 1).

The risk of soil consumption by children can be determined from the estimated lowest observed adverse effect level (to produce acute gastrointestinal symptoms) for a single dose of ingested Cd, estimated at 43 μg/kg body weight.[50] A 10 kg child would need to eat 108 g dry matter of soil with 4 μg Cd/g to reach this dose. The background intake of Cd (12–84 μg/day in urban areas, 10–60 μg/day from food and water) is much higher than from contaminated soil.

The greatest risk of ground contamination was probably from material washed off the dispenser in the field before it was returned to headquarters, as operators were instructed that "gross contamination around the dispenser on the trailer will be brushed off and washed down before departing". However, the sites are not sufficiently precisely identified in the reports to permit remedial action, and in any case, in the intervening 35–48 years it is to be expected that some of the ZnCdS will have been subjected to chemical weathering and transmutation, broken down by bacteria, and leached from the surface soil. Any material that resisted breakdown for this period should be so insoluble as not to pose a health hazard.

A further possible risk was to four Ministry of Defence officials that operated disseminators, as the respirators may not have protected them against the particles, which had median diameter 1.5 μm and density 4 g/cm^3. Two disseminators have survived and are in good health, one died aged 73 of a heart attack, and the final operator could not be definitively traced but is thought to be alive. The building on the Porton Range used for storing ZnCdS was destroyed at the end of the programme. Operators probably risked damage to eyes and exposed skin from ultraviolet light when counting ZnCdS particles, but this seemingly did not happen.

In conclusion, between 1953 and 1964, ZnCdS particles were disseminated from static sources, vehicles, ships, and aircraft by the Ministry of Defence. In long range trials, the inhaled dose during the most severe case was small (0.13 μg Cd). Land based trials did not significantly add to soil Cd, except close to the dissemination point. Risk to the public is therefore considered negligible. People involved in dissemination, who would have been exposed to large amounts of Cd, had no ill effects.

Table 4 Approved programmes of trials† of dissemination of ZnCdS from aircraft, 1960–4, where reports of the trials (and indication as to whether or not they took place) are unavailable

Programme number	Proposed location	Trials proposed (n)	ZnCdS/trial (kg)	Total amount ZnCdS (kg)
23/60	Not stated	3	91	273
2/61	Cardington	4	68	272
	Cardington	6	14	84
24/62	Cardington	6	45	270
10/63	Cardington	2	136	272
2/64	Norwich	4*	54	216
			TOTAL	1387

*Dates of three of the four proposed trials were open to cancellation.
†Excludes three proposed trials at Netheravon Airfield (programme 14/63) where total proposed releases were 0.75 kg.

Key messages

- The maximum possible inhaled dose as a result of the Ministry of Defence trials is small relative to background concentrations of inhaled cadmium.
- The increase in cadmium loading of soil near the points of dissemination from static land based sources is small, except in the immediate vicinity of the disseminators.
- There were no adverse effects on people operating the disseminators, who may be expected to have inhaled larger doses than the exposed population.

Policy implications

- Excessive cadmium intake has potentially harmful effects on humans, but the contribution from Ministry of Defence trials during the cold war was very small in comparison with background exposure. There is no need for public concern over the Ministry of Defence disseminations.

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