EPA 560/6-81-005

EPIDEMIOLOGY STUDIES
MAGNETIC LUNG MEASUREMENTS IN RELATION TO OCCUPATIONAL EXPOSURE IN ASBESTOS MINERS AND MILLERS OF QUEBEC

JANUARY 1981
FINAL REPORT

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF PESTICIDES AND
TOXIC SUBSTANCES
WASHINGTON, D.C.

EPA 560/6-81-005
January 1981

MAGNETIC LUNG MEASUREMENTS IN RELATION TO OCCUPATIONAL EXPOSURE IN ASBESTOS MINERS AND MILLERS OF QUEBEC

by

David Cohen[1], Thomas Crowther[1]

~~Graham Gibbs~~[2], ~~Margaret Becklake~~[2]

1. Massachusetts Institute of Technology
   Cambridge, Massachusetts

2. ~~McGill University~~
   ~~Montreal, Canada~~

Project Officer
Jane E. Keller

Health and Environmental Review Division
Office of Pesticides and Toxic Substances
Washington, D.C. 20460

U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

DISCLAIMER

ACKNOWLEDGEMENTS

The authors wish to thank the Quebec asbestos mining industry and their employees for their cooperation, as well as the Institute of Occupational and Environmental Health of the Quebec Mining Association.

The authors are grateful to Mr. Ed Givler for his help during the early phases of this project, to Mrs. Eleanor Pyle for her encouragement and editorial help, and to Mrs. Donna Neuberg and the MIT Statistics Center for their statistical evaluation of the data. ~~M. R. Becklake is a Career Investigator of the Medical Research Council of Canada.~~

Last we would also like to thank Emanuel Landau, Ph.D., Lenora Barnes, M.P.H., and the entire staff at the American Public Health Association; Joseph Seifter, M.D., Charles Poole, M.P.H., of the U.S. Environmental Protection Agency for their cooperation and support.

The experimental measures and initial data analysis of this project were supported by NIH grant #HL17543 and NSF grant #APR-761019.

ABSTRACT

Fe_3O_4 particles (magnetic) are often attached to asbestos fibers (non-magnetic) in the primary asbestos industries; therefore, a measurement of Fe_3O_4 could help determine the amount of asbestos in the lungs of workers in these industries. As a first assessment of this method of determining retained dust, magnetic measurements were made of the amount of Fe_3O_4 in the lungs of 115 miners and millers of chrysotile asbestos. The performance of these measurements at an industrial site was found to be feasible and practical. A relatively large amount of Fe_3O_4 was seen in the lungs of those with welding experience, which masked the Fe_3O_4 contributed by asbestos, therefore this group was considered separately. For the remainder (non-welders), the amount of Fe_3O_4 was plotted against a total dust exposure index which was available for each individual. The correlation between these quantities was not high, but was statistically significant at the 0.01 level. For the non-smokers within that group, the correlation was higher and the amount of Fe_3O_4 was relatively greater. These results suggest that the magnetic measurement of a chrysotile miner and miller reflects, at least to some extent, the amount of asbestos in his lung; the scatter could be due to individual differences in deposition and clearance, to which this measurement should be sensitive. These results are also consistent with the possibility that less dust is deposited or retained in smokers than in non-smokers.

INTRODUCTION

During the past decade, a method has been developed to measure ferrimagnetic dust in the human lung (Cohen, 1973, 1975). In this method, the lungs of the subject are first magnetized by an external magnetic field. Then, after the external field is removed, the remanent field produced by the magnetized particles is measured over the subject's torso; this yields the amount of this dust in the lungs. Because chrysotile asbestos often occurs with attached ferrimagnetic Fe_3O_4 particles, and preliminary measurements of several chrysotile miners and millers had revealed a measurable amount of Fe_3O_4 in their lungs, the question arose: Can the magnetic method be useful in determining the amount of asbestos in the lungs of miners and millers? The study reported here begins to answer that question.

We concentrated on mining and milling because the Fe_3O_4 content of asbestos is high at this primary stage (Gibbs, 1971). In particular, we concentrated on the miners and millers of chrysotile asbestos in Quebec. For this well-studied population, previously the amount of asbestos in a worker's lung had been inferred from his total dust index, defined as (concentration of airborne dust) x (period of exposure), summed over his various jobs (Gibbs and Lachance, 1972). Epidemiological studies have shown a relationship between respiratory abnormality and this index (Becklake et al., 1972; McDonald et al., 1972; Rossiter et al., 1972). However, in some of these studies the correlations, while statistically significant, have been low. This may be due to the indirect nature of this index, which does not take into account individual variations in dust deposition and clearance in the lung. The magnetic method, while it has its own drawback of being completely dependent on the ratio of Fe_3O_4 to asbestos, may nevertheless be more direct. Our main objective was to examine the relationship between the amount of Fe_3O_4 in the lungs and the total dust index. If the amount of Fe_3O_4 was indeed related to the amount of asbestos in the lung, then we would expect at least some correlation with this dust index.

The remanent field produced by the lung particles is very weak

($\sim 10^{-5}$ gauss), in comparison to the background earth's field in which it is measured (~ 1 gauss). This field must therefore be measured with care and attention. While it can readily be measured in a well-equipped laboratory, we previously had little experience in measuring this field at a distant industrial site, such as at the mining town where this study was performed. Hence our second objective was to see if such on-site measurements are practical, not only for possible use in the primary asbestos industries, but for other "magnetic" industries as well.

The measurements were made in 1974, and preliminary results had been reported (Cohen, 1978). Following this study, other magnetic studies of occupational groups were performed. These include two studies of welders (Kalliomäki et al., 1978; Freedman et al., 1979) and a study of coal miners (Freedman et al., 1980). In addition, a magnetic study of stone workers is being completed (M. Kotani of Tokyo Denki University, personal communication). However, in none of these studies was the relationship examined between magnetic reading and dust exposure, nor was the practical aspect evaluated. In addition to these studies, magnetic studies of only small occupational groups have been described (Cohen, 1978).

MATERIALS AND METHODS

The Group Studied

The target group had already been selected for certain lung function measurements (Peress et al., 1977), and were without radiologic abnormality in that their most recent chest film was read as 0/0. This group contained both smokers and non-smokers, an age range from 26-50, and a wide range of total dust indices. These indices applied only to exposures up to 1967; the period of 1967-74 was not included, but the omission is not likely to be serious because the dust level had become reduced by the late 1960's. Unfortunately, the general nature of the grouping changed after measurements began, when it was seen that workers with welding exposure had a relatively large amount of Fe_3O_4 in their lungs, which could mask the Fe_3O_4 from asbestos. We therefore divided the original group of 115 into those with and without welding exposure. The relation between magnetic readings and total exposure index was investigated only for the non-welding group, now reduced to 51. For the remainder, our efforts were salvaged by estimating their exposure to welding dust and examining the relationship between the amount of Fe_3O_4 in their lungs and this exposure; if the Fe_3O_4 amount was a reflection of occupational exposure, we would again expect to see a correlation between the two.

The divisions within the group are given in Table I. Those called smokers included 11 who were ex-smokers at the time of this study; they were included because their smoking had taken place when most of their dust was inhaled, some years earlier, hence it would have affected their response to dust. Welders were divided into those with only a small (<0.1 year) and those with a greater (>0.1 year) exposure to welding dust, to allow various correlations. However, it is seen that some correlations would be limited by very small sub-groups, such as 5 or 12 welders.

Table I. Divisions Within the Group Studied

	Smokers	Non-smokers	Total
Welders (>0.1 year)	33	12	45
Welders (<0.1 year)	5	12	17
Non-welders*	33(33)	20(18)	53(51)
Total	71	44	115

*Numbers in parentheses are those non-welders for whom total dust exposure indices were available.

Magnetic Measurements

We measured not only the amount of Fe_3O_4 in the lung, but also its crude distribution within the lung; in addition, we measured two quantities which are unique to magnetic particles. During the application of the external field, the particles are both magnetized and become rotationally aligned with this field. However, their rotation is impeded by their viscous environment; we measured a quantity involving this impedance, called the apparent viscosity. After magnetization, the remanent field produced by the particles is not steady but always decreases in time, typically by a factor of three or four in an hour. This decrease, called relaxation, is due to random rotations imparted to the initially-aligned particles by local motions in the lung; because the remanent field is the vector sum of the fields from all particles, it becomes reduced as the particles become randomized. We measured the rate of relaxation. Our purpose in measuring these auxiliary quantities was to see if they were useful in measurements of occupational groups.

The magnetic measurements were made during each subject's visit, mainly for his lung function tests, to a clinic in the town of Thetford Mines. Between tests the subject made an initial 15-minute visit to the magnetic station in the clinic, during which most of our measurements were made. If he showed enough Fe_3O_4, he then returned about 20 minutes later for a 5-minute relaxation measurement; in some cases the schedule allowed a third similar visit.

During the initial visit, the subject changed from his clothing into special shorts, thereby removing all magnetic items from his person (zipper, shoes, etc.); dental plates, which are always magnetic, were also removed. In order to be magnetized, the subject was placed between two coils, as shown in Fig. 1(A). These coils were powered by two car batteries, and generated a magnetic field which was uniform over the lung to ± 10%. The subject was magnetized twice. The first was only for viscosity purposes; a field of 400-gauss strength was applied for only 0.35 seconds (called the short pulse), which magnetized the particles but only partly rotated them. After their remanent field was measured, the subject received the second, main magnetization; a 750-gauss field was applied for 30 seconds (the long pulse), which was enough strength and time to produce complete alignment of particles. In Fig. 1(B), the remanent field due to the magnetized particles is seen to be oriented almost horizontally, called the z-direction, at the chest and back; the field is called B_z when measured over those areas.

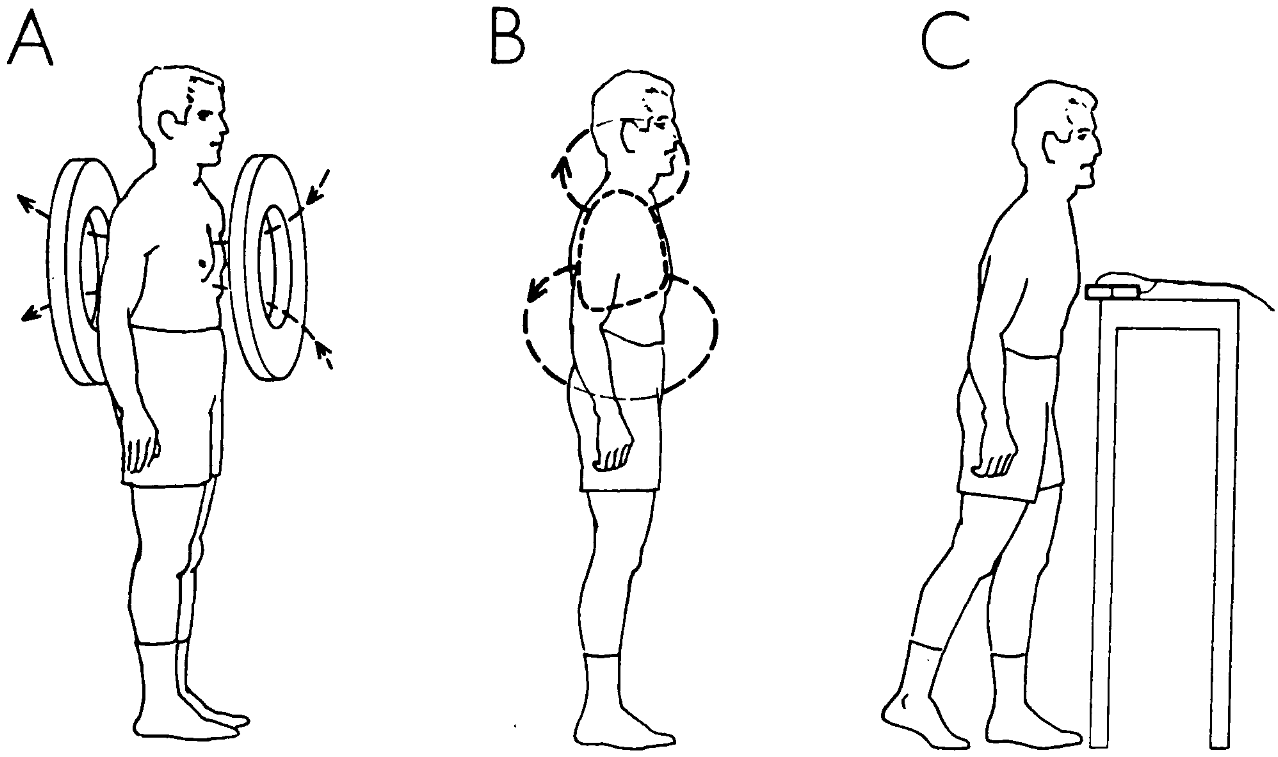

Fig. 1. Sequence of magnetization and measurement. (A) Subject being magnetized by the external field (broken lines); this field both magnetizes and aligns the particles. (B) The remanent field around the torso produced by the magnetized particles. Over the chest and back the field is approximately horizontal, and is called B_z. (C) Subject performing a measurement of B_z by moving up to the gradiometer, which is fixed to the table. He is shown at the "near" position of his far-near-far motion. Not shown here is a plastic shield which is mounted up from the floor, and prevents him from touching the fluxgate and causing an artifact.

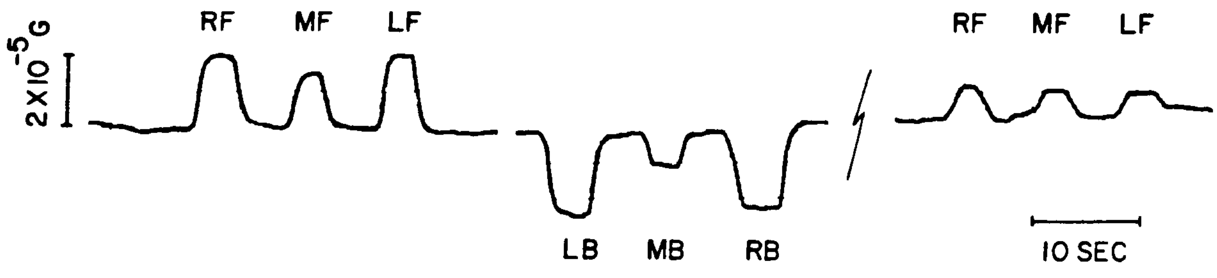

Fig. 2. An example of the gradiometer output, due to measurements of a subject's B_z at the lung points. The first three measurements are at the subject's right front (RF), middle front (MF), and left front (LF), recorded about 30 sec after magnetization; the three back points (LB, MB, RB) were recorded 15 sec later. The B_z's at R and L are larger than at M because the detector views more Fe_3O_4 there. The final three signals (back points omitted) were recorded 27 min later; the typical decrease of B_z due to relaxation is seen, as well as some baseline (background) disturbance.

To measure B_z, we used the magnetic detector called the fluxgate. This detector is compact, simple to use, and has a suitable sensitivity. It can measure fields down to 5×10^{-7} gauss in the 0-3 Hz bandpass in which it was used, corresponding to the detection of about 0.05 mg of Fe_3O_4 in the lungs. In dealing with the problem of the magnetic background, the steady and fluctuating backgrounds are considered separately. To deal with the steady background, the detector was always rigidly fixed in position, and the subject moved up to the detector for a measurement; in this way the change in detector output was only due to the subject's B_z. The problem of the fluctuating background, due for example to moving cars, (which act as large moving magnets), was minimized by using the fluxgate in the gradiometer mode as follows. The output of the model we used (#MF-5000, Automation Industries, Ltd.) is the sum of outputs from its two identical probes; they were mounted in-line about 10 cm apart, (horizontally, as shown in Fig. 1(C)), and oriented oppositely so that the output was the difference in B_z between them. Thus a fluctuating B_z produced by a distant source was largely cancelled, while the B_z from a subject's lung was not cancelled because it was much larger in the nearer than the further probe. The fluctuating background in this mining town was negligible when dealt with in this way.

For a measurement the subject first stood out of range of the detector, then moved inward and placed a point of his torso at the detector as shown in Fig. 1(C), then stepped back again. The detector has a bell-shaped response curve in angle, with the maximum at the 0° or z-line and a half-maximum at about ± 22°, corresponding to about ± 3 cm at the lung. Measurements were made at three marked points on the chest and three corresponding points on the back, called the six lung points; the chest points were on a horizontal line 10 cm above the xiphoid, one at the midline and two 10 cm on each side, at about the nipples. In addition, measurements were made at the chin and three abdomen points, 20 cm below the chest points. Measurements at these non-lung points were made in order to detect any magnetic contamination occasionally present in the abdomen and the head, which could mask the Fe_3O_4 in the lung. When such contamination was seen, it could usually be demagnetized with a hand-held magnetic tape eraser; in five subjects the contamination was large enough to resist this procedure, and they were not included in the study.

Processing the Magnetic Data

We here describe how the values of B_z from the six lung points were converted into the amount of Fe_3O_4 in the lung and the auxiliary quantities. The B_z values were first summed in these various ways: ΣF (three front B_z's), ΣB (three back B_z's), ΣM (two middle B_z's), ΣL (two left B_z's), ΣR (two right B_z's), and $\Sigma 6$ (all 6 B_z's). By using the relaxation rates (see below), these sums, from both short and long pulses, were extrapolated back to 0-time (end of the magnetizing pulse). Next, the long-pulse sums were combined in various ways to yield the crude distributions in the lung; $\Sigma L/\Sigma R$ indicates the amount of Fe_3O_4 in the left lung compared to the right, $2\Sigma M/(\Sigma L + \Sigma R)$ indicates the amount in the middle compared to the average side, and $\Sigma F/\Sigma B$ is the front/back ratio.

To calculate the amount of Fe_3O_4, we first consider the simplest relationship between this quantity and B_z; this is when all the Fe_3O_4 in the lung is imagined to be compressed into a point source, called the magnetic dipole; for which

$$B_z = 2 I m z^{-3} \qquad \text{or} \qquad B_z / (2 I m) = z^{-3} \qquad (1)$$

where B_z is in gauss, m is the Fe_3O_4 mass in grams, and z is the distance to the field point in cm. I is a property of the magnetic dust called the magnetization (in emu/gm); based on our measurements of laboratory samples, and on literature values, we chose I = 10, so that eqn. (1) becomes $B_z/20m = z^{-3}$. For large z, an actual lung behaves as eqn. (1), with the z^{-3} falloff. However, for z < 20 cm, the B_z dependence on z is the curve shown in Fig. 3(A). To use this curve, if there were only one probe, say the near probe of the gradiometer, we would simply use the z for that subject to determine the ordinate $B_z/20m$, and knowing B_z, we would solve for m. However, because of the far probe of the gradiometer (z+8.6 cm), we use the difference of the ordinates, called F_g, so that

$$F_g = (1/20m)\,(B_z - B_{z+8.6}) \qquad (2)$$

and if we replace the latter term, which is the gradiometer reading, by the average $(1/6)\Sigma 6$ (in units of 10^{-7} gauss) we obtain our basic formula

$$m = (8.3 \times 10^{-3}\,\Sigma 6) / F_g \qquad (3)$$

where m is now the amount of Fe_3O_4 in mg. The error involved in using this formula is due to two sources. The first is a probable error of ± 30% in I; since I is a constant for all subjects, this error does not affect their relative m. The second is a probable error of ± 30% in F_g; this is due to uncertainty in individual lung spacing, hence this is the relative error in m for the data presented here.

For the viscosity quantity, we defined and used this term: apparent viscosity = $\Sigma 6_{long} / \Sigma 6_{short}$, which should increase with the viscosity experienced by the particles; however, it would also be sensitive to the shape and size of particles. In laboratory measurements of this type of quantity, we found it to be reproducible for an individual, but it does not correlate with obvious variables, such as smoking or the residence time of Fe_3O_4 in the lung.

Relaxation curves (B_z vs time) have been well studied; they have a characteristic mathematical shape (Cohen, 1974, 1978) and a dropoff rate which depends on the residence time of Fe_3O_4 in the lung and on smoking. The shape of the curves is seen in Fig. 3(B); recently inhaled Fe_3O_4 results in a rapid dropoff such as the lowest curve of Fig. 3(B), while Fe_3O_4 inhaled years ago results in a slower dropoff, such as one of the upper curves. Smokers who have recently inhaled Fe_3O_4 show a much more rapid dropoff than non-smokers (Cohen et al., 1979). It would seem, therefore, that the relaxation rate of these workers might reflect both the residence time of Fe_3O_4 in the lung, and the amount of smoking. Because of time restraints, which allowed only two or three B_z measurements following long-pulse magnetization, the following system was chosen to quantify the relaxation. Five relaxation groups were arbitrarily defined, as shown in Fig. 3(B). Two measurements $>$20 min apart were usually enough to place a subject in a particular group; three or more measurements yielded increased accuracy and allowed divisions within the group. Once the relaxation group was determined, the various sums of B_z could be extrapolated back to 0-time.

The Indices of Exposure

Dust sampling had been carried out since 1948 at various locations in the local mines and mills, using the midget impinger. This method yields the density of respirable dust in the air, where the dust here consists of both asbestos fibers and other particles. Using this density and the

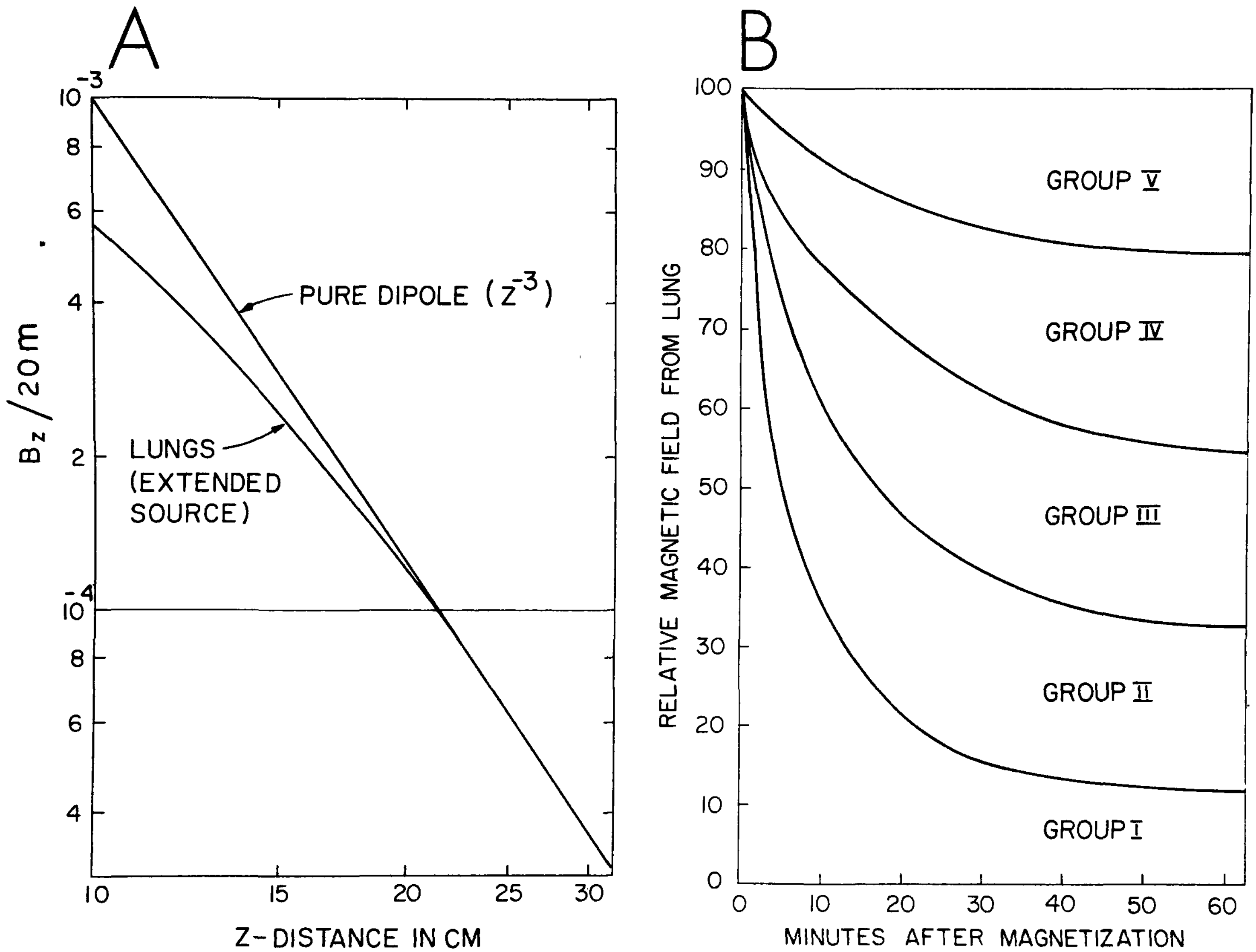

Fig. 3. Curves used in processing the magnetic measures. (A) Falloff from a dipole source (z^{-3}) and from an extended lung. The extended lung falloff is an average of falloff measurements from various subjects. The distance z is from the lung center to the field point, estimated from the thickness of the subject's chest. (B) The five relaxation groups which are used here. These are bounded by four relaxation curves of characteristic shapes derived from actual, measured curves; however, the four dropoff rates are arbitrarily chosen.

month-by-month employment record of each worker, a total dust exposure index was calculated, defined as (density) x (years worked at this location, corrected to a 40-hour working week), summed over each job held by the worker, up to the end of 1966. The index is given in units of (millions of particles/cu ft) x (years), or mpy/cf. That the termination of the index by the end of 1966 does not seriously affect its use for 1974 supported by data on the steady decrease in dust density in the mills; for example, it had fallen from an average of 75 mp/cf in 1948 to 10 mp/cf in 1966, with reductions thereafter.

The exposure index for welding was derived more crudely, without dust sampling. The index we used was simply the period of welding exposure in years, corrected to a 40-hour working week; e.g., for a 10% work-time exposure for 20 years, the exposure index was 2.0 years. A welding history was obtained by careful questioning of each worker during the clinic visit and, in cases of ambiguity, by telephone follow-up. In contrast to the total dust index, the index used here applied up to the time of this study. If a worker had any welding exposure whatever, for example if only to nearby welding, he was grouped by us with the welders. Table I, therefore, shows 17 "welders" with exposure of only <0.1 year. We included torch cutting, often used in the mines, as a welding procedure.

RESULTS

The amount of Fe_3O_4, its crude distribution within the lung, the apparent viscosity, and the relaxation rate were readily measured; their distributions within the group* are given in Figs. 4 and 5, and in Table II. Fig. 4 shows that the amount of Fe_3O_4 in the lungs of welders is indeed greater than in non-welders, as we had seen during the measurements. The average amount of Fe_3O_4 in the lungs is 1.3 mg for a non-welder, and 7.8 mg for a welder; if the first interval is excluded, the amounts increase to 1.7 and 8.3 mg. There is therefore about fives times more Fe_3O_4 in the lungs of the welders of this group.

The results of one type of distribution measurement of Fe_3O_4 within the lung, the ratio of left/right, is shown in Fig. 5. The fact that less

---

* As distinct from Fe_3O_4 distribution within the lung.

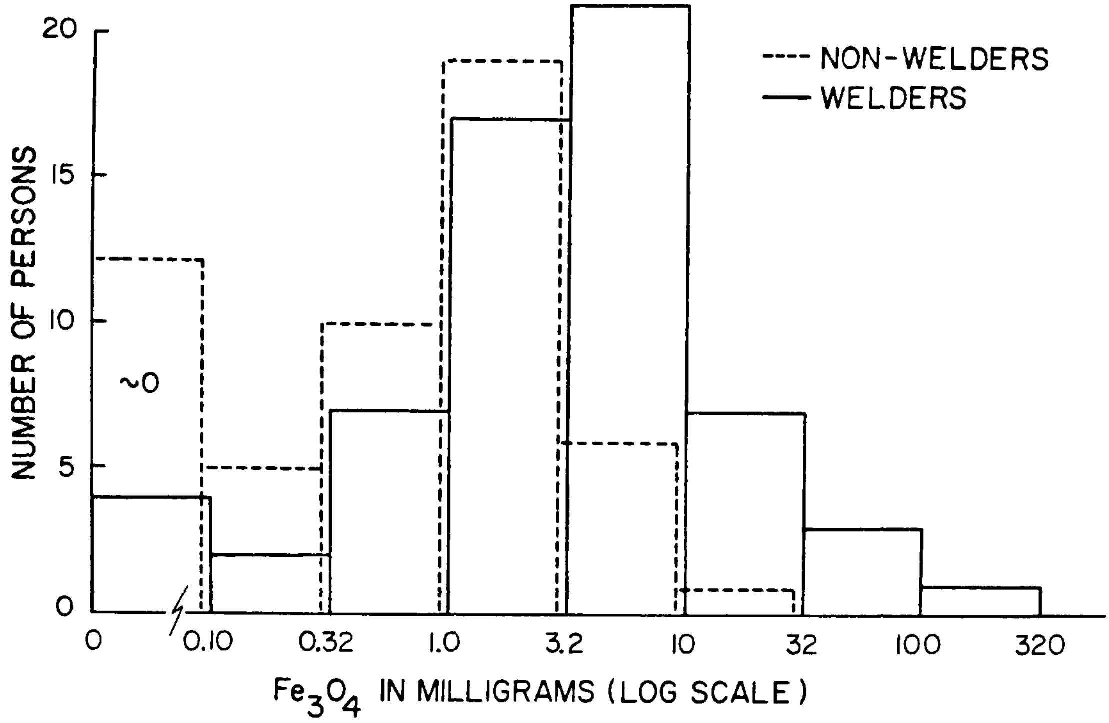

Fig. 4. Distribution within the group of the amount of Fe_3O_4 found in the lungs of the 53 non-welders, and the 62 welders. A log scale is used, except for the first interval which extends down to and includes zero. This interval is elevated for the non-welders because it contains office workers, and for the welders because it contains borderline cases where it was not certain that there had been exposure to welding dust.

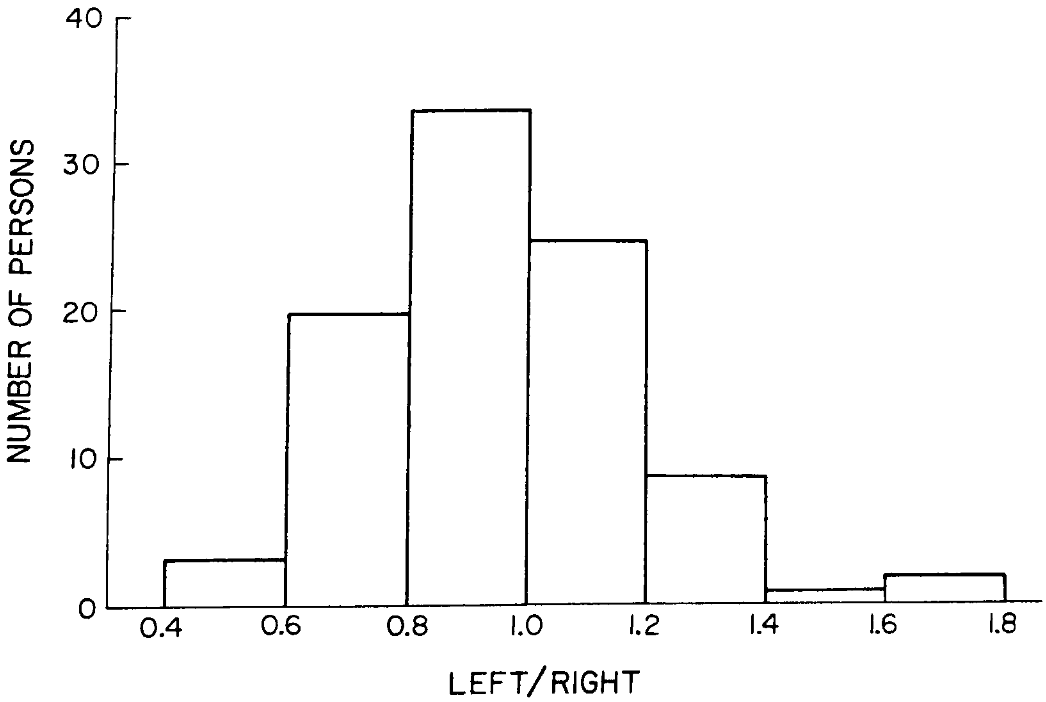

Fig. 5. Distribution within the group of the ratio of the remanent field on the left side of the torso to that on the right ($\Sigma L/\Sigma R$). On the average, the left side produces less field, hence contains less Fe_3O_4 than the right side. This is because of the reduced volume of lung on the left, due to the heart.

dust is seen on the left, demonstrates that the magnetic method is capable, by measurements at an industrial site, of yielding at least some distribution information. The large left/right spread is due to our crude B_z measurements; if the measurements would have been made with more accurate positioning of each subject, then the spread would have been far narrower. The remaining magnetic data are shown in Table II, along with data on dust exposures. For the magnetic quantities, the total number of subjects in each row (All) is limited to those who contain enough Fe_3O_4 for this type of measurement.

For the middle/side ratio, the table shows a most probable value of about 0.5; this indicates the smaller amount of Fe_3O_4 "seen" by the detector at the middle, where there is almost no lung, in comparison to the side. Again, the method reveals at least some distribution information. However, the meaning of the most probable value of about 0.7 for the ratio of front/back is not as obvious: although there is more posterior than anterior lung, there are also differences in lung-to-detector spacing between front and back, as suggested by one of the correlations presented below. The large spread about the 0.7 value is again due to coarseness of the z-spacing, to which this ratio is sensitive. In the next quantity, the relaxation group, the coarseness has been reduced by averaging ($\Sigma 6$), and the spread about the most probable group II is actual Fe_3O_4 behavior. This applies to the apparent viscosity as well, where the most probable value is about 1.8.

For the dust exposure data, the distribution within the group is different for the years welding in comparison to the total dust index. While they both have a large number in the first interval, due to "borderline" welders for the former and office workers for the latter, the distribution for the latter has an obvious dip in the middle interval. This was a deliberate choice in the makeup of the group for the lung function measurements; most workers were selected to have either low or high exposure, but a small group was selected at the mid-level as well.

To visually examine the relationship between the amount of Fe_3O_4 and the total dust exposure index, these quantities are plotted against each other in Fig. 6 for all the non-welders, and in Fig. 7 for these non-welders who are non-smokers. In both figures it is seen that there is considerable scatter, with no obvious correlation between the two quantities;

Table II. Number of Persons vs. Magnetic and Dust Quantities

Quantity	Definition	Intervals							All
Middle/Side	$2\Sigma M/(\Sigma L+\Sigma R)$	0.0-	0.2-	0.4-	0.6-	0.8-	1.0-	1.2-	
	number	0	4	39	32	20	2	0	97
Front/Back	$\Sigma F/\Sigma B$	0.4-	0.6-	0.8-	1.0-	1.2-	1.4-	1.6-1.8	
	number	7	27	26	16	9	1	1	87
Relaxation Rate	group		I	II	III	IV	V		
	number		6	40	15	2	0		63
Apparent Viscosity	$\Sigma 6_\ell/\Sigma 6_s$	< 1.0	1.0-	1.4-	1.8-	2.2-	2.6-	3.0-3.4	
	number	0	7	20	20	11	10	3	72
Welder's Exposure	years*	< 0.1	0.1-	0.32-	1.0-	3.2-	10-	32-	
	number	17	8	13	18	2	4	0	62
Total Dust Exp. Index	mpy/cf*	0-3.2	3.2-	10-	32-	100-	320-	1000-	
	number	21	8	27	10	26	20	0	112

*Intervals are in log scales except first interval

this applies to both the points clumped near the origin, and the more visible points. The same scatter and low visible correlation is seen in the welding plot, in Fig. 8. In order to see if the correlations between these various quantities were indeed as low as appears visually, a statistical analysis was performed; the analysis was extended to include correlations between any of the variables in this study where there might be some basis for correlation. The analysis involved three computations. The first was least squares, which provided the correlation coefficient r and a straight line; the second was of the Spearman's rank correlation coefficient r_s (Snedecor and Cochran, 1967); the third was a robust regression to provide a straight line, using an iteratively weighted procedure in which the weights are inversely proportional to the relative size of the residuals in the previous procedure

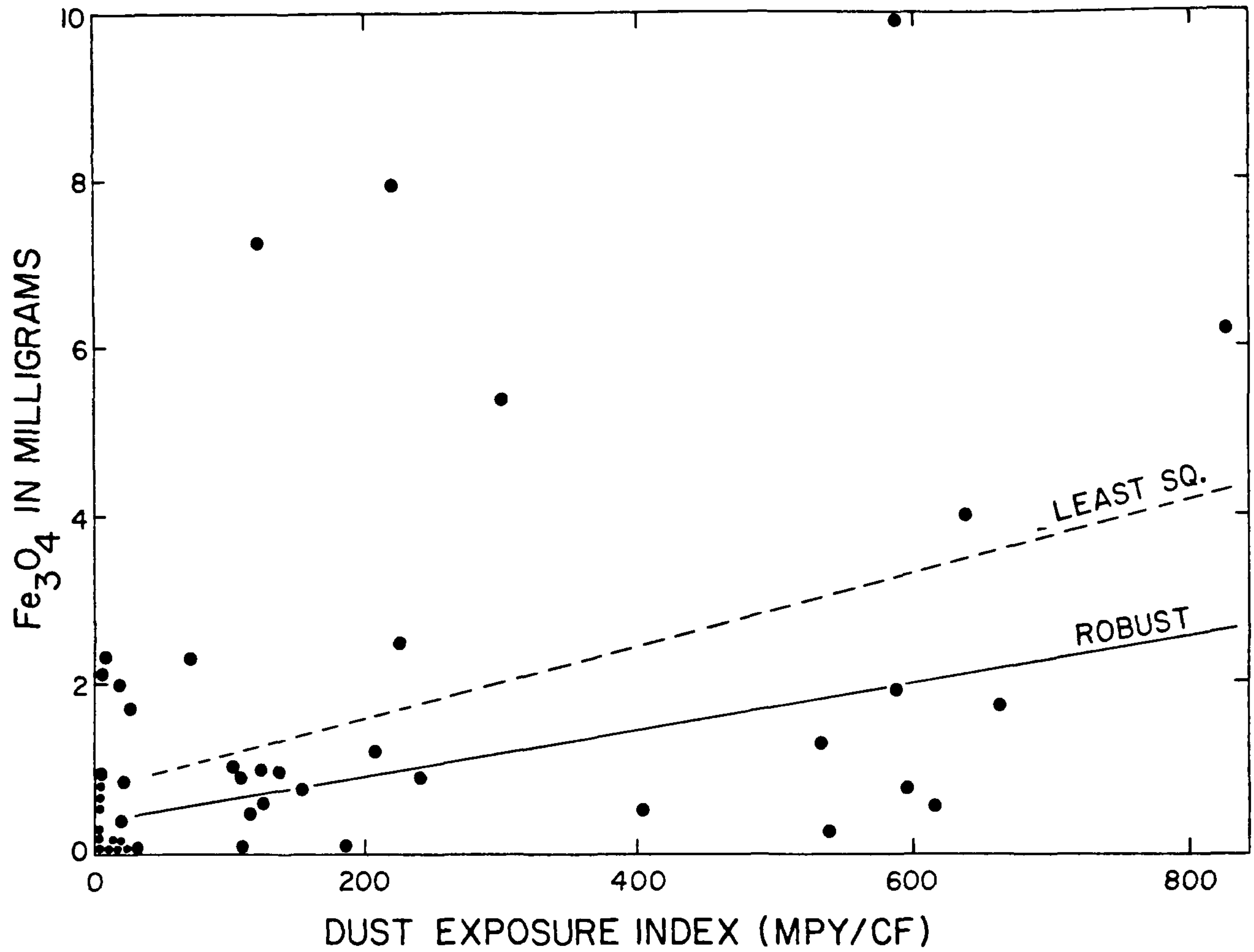

Fig 6. Amount of Fe_3O_4 in the lung of each worker vs his total dust exposure index, for the 51 non-welders. Six points near the origin have been omitted here. Although visual inspection shows no obvious correlation, Spearman's rank correlation gives $r_s = 0.50$ and the least-squares regression gives $r = 0.45$; both are significant at the 1% level. The straight lines are due to the least squares fitting of the data, and the robust regression procedure.

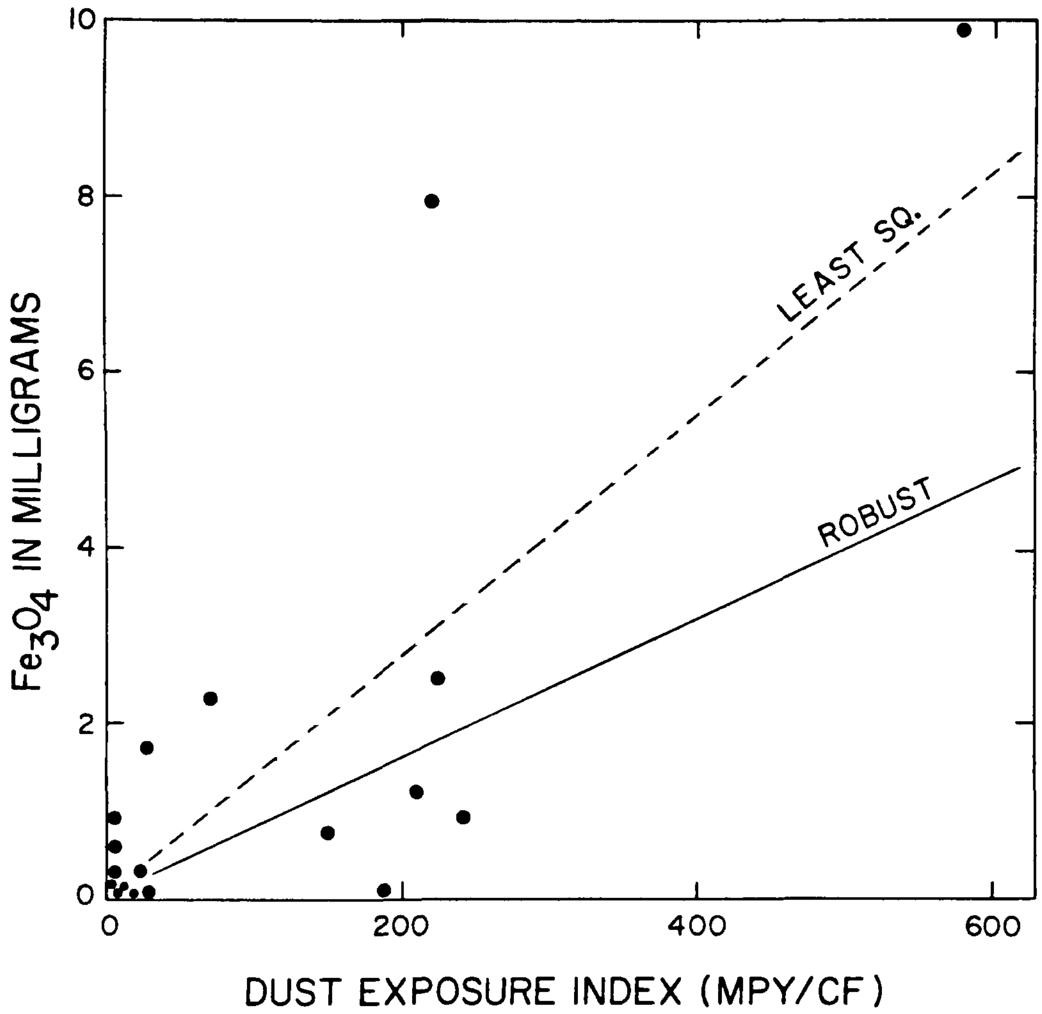

Fig. 7. Amount of Fe_3O_4 vs. total dust exposure index, for the 18 non-welders non-smokers. Again visual inspection shows no obvious correlation, but Spearman's rank correlation gives $r_s = 0.62$ and least-squares regression gives $r = 0.80$, again significant at the 1% level. The line slopes are greater than in Fig. 6, therefore these non-smokers appear to have more dust in their lungs than the smokers.

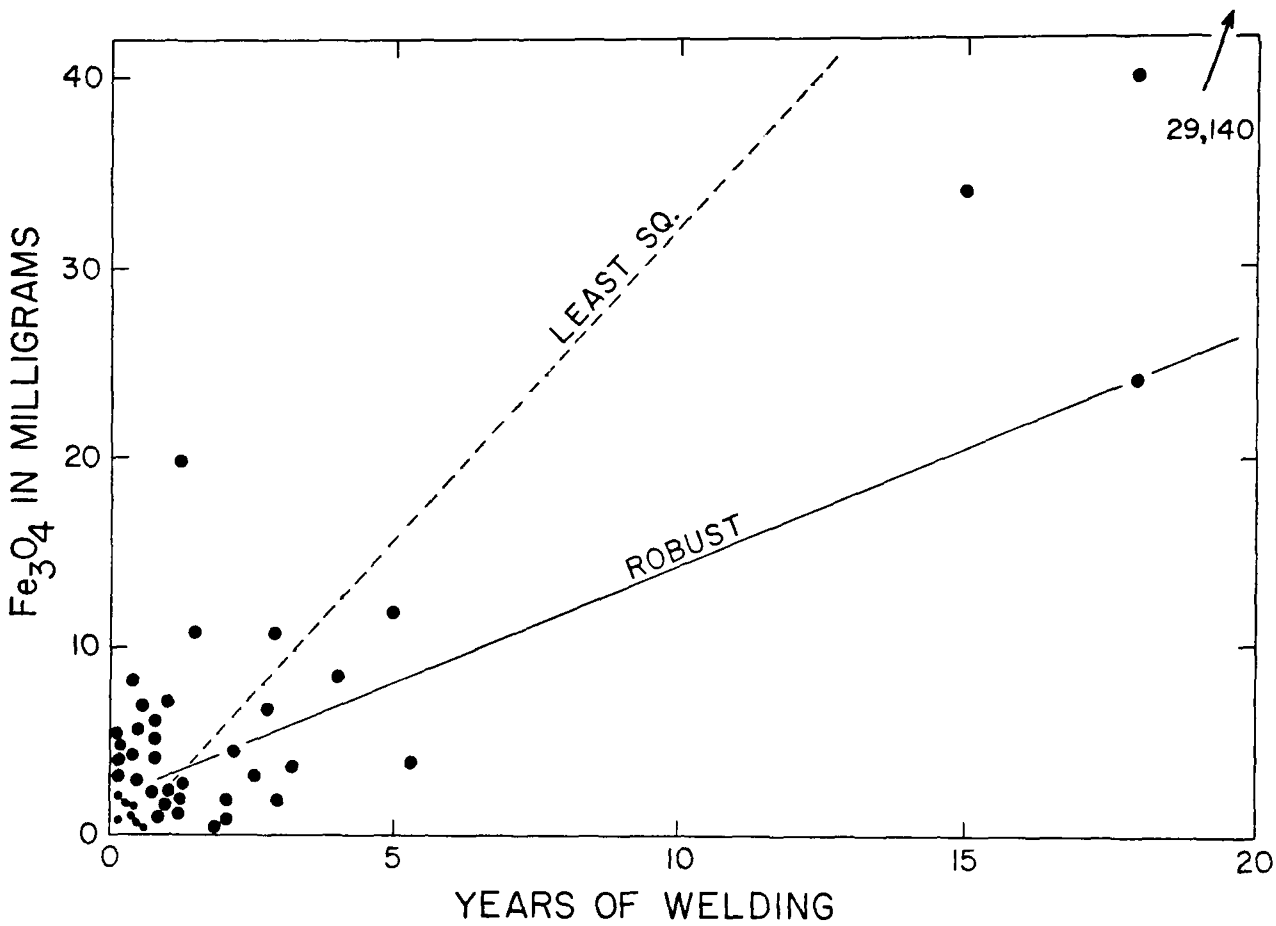

Fig. 8. Amount of Fe_3O_4 vs. years of exposure to welding dust, for the 45 asbestos workers with >0.1 years of welding. The arrow indicates that one point is off the figure, at the upper right, with 29 years and 140 mg. Again visual inspection shows no obvious correlation, but Spearman's rank correlation gives $r_s = 0.37$ (significant at about the 1% level), and least-squares regression gives $r = 0.88$ (high significance). The least squares line is pulled up by the high point.

Table III. Correlation Coefficients r_s due to Spearman's Rank Analysis

	Group	Chest Thickness	Relaxation Rate	Fe_3O_4 Density	Fe_3O_4 Amount
Vital Capacity	all			low(104)†	low(106)
	non-sm.			low (39)	low (41)
Front/Back	all	0.38 (88)**	low (76)		
	non-sm.		low (28)		
Middle/Side	all	0.21 (93)*	low (76)		0.22 (93)*
	non-sm.		low (28)		low (32)
Appl. Viscosity	all		low (64)	0.25 (67)*	0.23 (72)*
	non-sm.			0.49 (18)*	0.47 (19)*
Relaxation Rate	all	low (76)		0.25 (72)*	low (77)
	non-sm.	low (28)		0.40 (26)*	low (27)
Cigarettes/Day	all		low (77)		
Years Welding	all		low (41)	0.58(109)**	0.55(115)**
	non-sm.			0.53 (40)**	0.50 (42)**
	>0.1 yrs.				0.37 (45)**
	>0.1 yrs. + non-sm.		0.64 (12)*		low (12)
Total Dust Index (only non-weld.)	all			0.47 (50)**	0.50 (51)**
	non-sm.			0.67 (18)**	0.62 (18)**

† r_s is simply called low (low correlation) if it is not significant at the 5% level; the number of cases is given in parentheses.

* significant at the 5% level

** significant at the 1% level or less

(Mosteller and Tukey, 1977). This method was appropriate because it is not sensitive to the many outlying points of our data to which the least squares regression is quite sensitive.

The results of the Spearman's rank correlations are given in Table III; the coefficient r_s is simply called "low" unless the correlation is significant at the level of 5% or less, (indicating a probability of 5% or less that this could have occurred at random). The chest thickness used in the table had been coarsely measured, with the subject's back at the wall. The relaxative rate had been quantified so that the number increased linearly with the relaxation group, and subdivisions within a group were also used. The density of Fe_3O_4 was the amount of Fe_3O_4 divided by the lung volume, obtained from their lung function measurements. The vital capacity (% of predicted value) was similarly obtained; it can be an early indicator of pulmonary abnormality due to exposure to asbestos dust, however the range is small in this group because of their 0/0 chest films. For the cases of direct interest (Figs. 6, 7 and 8), we here give least-squares results. For the amount of Fe_3O_4 vs. the total dust index, $r = 0.45$ for all non-welders (51) and $r = 0.80$ for those that are non-smokers (18); these are both significant at lower than the 1% level, in agreement with the rank correlation. For the amount of Fe_3O_4 vs. the years of welding, $r = 0.88$ for those welders with >0.1 years exposure (45); this is certainly significant at lower than the 1% level. Further comments on this table are made below.

DISCUSSION

If the ratio of Fe_3O_4/asbestos was always a constant, both in respirable dust and after deposition in the lung, then this study would not have been necessary; a measurement of the amount of Fe_3O_4 would directly give the amount of asbestos in the lung. However, while this ratio is quite constant for the airborne dust at most locations of the Quebec mines and mills, it is not known if it changes in the lung. The ratio in more than 100 samples from the mines and mills was recently measured (O. Djamgouz of Laurentian University, personal communication); the ratio of Fe_3O_4/chrysotile was always found to be in the range of 2-5% by weight, where the lower the grade of asbestos, the higher the percentage. In the lung, however, the Fe_3O_4 particles probably become detached from the fibers to which they were stuck, and may clear out differently from the fibers; this is suggested by the fact that chrysotile fibers in the lung are known to dissociate, after some months or sooner, into fibrils (Suzuki and Churg, 1969). Further, there may be some inhaled Fe_3O_4 dust which was not attached to fibers; and which may also clear out differently. If the clearance rates are indeed different, then the ratio of Fe_3O_4/asbestos will change in time; the greater the difference in clearance rates and the variation in this difference from person to person, then the greater the uncertainty in the magnetic method for determining the amount of asbestos.

Assuming that the ratio is not constant, the straightforward way to find out how well the magnetic method can determine the amount of asbestos would have been to magnetically measure autopsied lungs of miners and millers, and correlate the amount of Fe_3O_4 with the actual amount of asbestos present. An alternative approach would have been to correlate the amount of Fe_3O_4 with lung abnormality in miners and millers; here we would have found out how well the magnetic method determines both the amount of asbestos and its biological effects, which is another issue. Neither way was available to us at that time, hence we chose a variation of the second approach. This was to find the correlation between the amount of Fe_3O_4 and a dust exposure index which does correlate with lung abnormality; namely the total dust exposure index. If the amount of Fe_3O_4 would correlate highly with the amount of asbestos, then at best we can expect a low but significant correlation between the amount of Fe_3O_4 and this total index: this is because the correlation is not high between this index and lung abnormality. On the other hand, if there was an intrinsically low correlation between the Fe_3O_4 and the asbestos, then we would expect the correlation between the Fe_3O_4 and the index to vanish.

Although the eye shows no correlation in Figs. 6 and 7, the statistical analysis does show a correlation which is low but statistically significant. This is compatible with a high correlation between the amount of Fe_3O_4 and asbestos, and incompatible with a low correlation between them. Stated otherwise, the magnetic method appears to indicate the amount of asbestos in the lung, at least to some extent; the relative Fe_3O_4/asbestos clearance rates do not appear to vary greatly from person-to-person. It follows that the large scatter in Figs. 6 and 7 must be due, in large part, to individual differences in deposition and clearance. The points well below the robust lines, for example, are due to less deposition or more clearance than normal (per unit of exposure), while the points well above the least squares line are due to more deposition or less clearance than normal.

It is tempting to speculate that those points very high off the line, say the two points near the upper left corner of Fig. 6, may represent individuals at increased risk, in the sense that their dust clearance mechanisms may be impaired. This would suggest that the magnetic method may be useful in the primary industries for screening of workers with supposed impaired clearance, hence at increased risk; although the dust levels are now reduced, impaired clearance may nevertheless result in enough Fe_3O_4 to be measured. In that regard, we note in Table III that the amount or density of Fe_3O_4 does not correlate with the vital capacity, the possible early indicator of abnormality; this strengthens the idea that the measurement of amount of Fe_3O_4 should be only for the purpose of determining the amount of asbestos, not its biological effects; the increased risk mentioned above would only be due to an increase of asbestos in the lung, not its effects.

The conclusion that Fe_3O_4 indicates in part the amount of asbestos is indirectly supported by the data on welders. Whether for all workers, as shown in Table III, or for welders with >0.1 years exposure (Fig. 8), there is a correlation between the Fe_3O_4 and the welding exposure which is statistically significant. Again, therefore, the magnetic method indicates, to some extent, the amount of occupational (welding) dust in the lung.

The large increase in the line slopes in Fig. 7 in comparison to Fig. 6 deserves comment. If statistically valid, this increase implies that smokers have less dust in their lungs than non-smokers, per unit of exposure. This would appear to be at variance with the recent result (Cohen et al., 1979) that smokers show impaired long-term clearance from the lung, hence retain more dust than non-smokers. Because the dust-count (alveolar) in that work did not begin until short-term clearance (from airways) had been completed, this discrepancy could be resolved if one assumes that smokers have far less alveolar deposition than non-smokers, perhaps because of different airway diameters, etc. Stated otherwise, if this result is valid, then in smokers perhaps less dust is deposited in the alveoli, but this alveolar dust is cleared away more slowly than in non-smokers. But how believable is the slope increase?

On the one hand, Fig. 7 has only 18 points, with the large slopes therefore depending on only a small number of special points. On the other hand, the slope increase exists for both the least squares and the robust lines. Perhaps we can only say that these results are consistent with smokers having less dust in their lungs than non-smokers, for the same exposure. Certainly we do not see here the large, reverse effect seen by Cohen et al; in that case both slopes in Fig. 7 would have been smaller by a factor of ten, which is clearly ruled out. It is unfortunate that the group of non-smoking welders was too small (12) to see if their slopes would also rise, compared to Fig. 8; Table III shows only a low correlation, hence the line is meaningless.

Because we see that the magnetic method can be useful in the primary asbestos industry for determining asbestos in the lung, we will comment about various other aspects of the magnetic technique which have shown up in this study, which may be of value in applying this method.

Concerning the practical aspects of these measurements, the fact that the Fe_3O_4 was readily measured in a mining town does not insure that other groups can easily be measured in other settings. It is a matter of magnetic signal/noise; more Fe_3O_4 in the lungs produces larger gradiometer signals which can override larger background noise. In this regard, the average amount of Fe_3O_4 in the lungs of different groups is important. We saw that the average in this group was about 2 mg and 10 mg for non-welders. We had measured some foundry workers while in the Thetford area and found the average to be 140 mg (!), while measurements at the MIT lab of workers in the secondary asbestos industries (finished products) yielded the much lower average of about 0.10 mg. Foundry workers can therefore be measured in an urban setting with high background; while workers in secondary asbestos industries could only be measured with a detector more sensitive than a fluxgate, in a magnetically quieter setting or with better gradiometer-cancelling techniques.

We next consider the correlations in Table III of the auxiliary magnetic quantities. There is a significant correlation between the front/back ratio and chest thickness, indicating the front B_z's are sensitive to the thickness of the muscle and fat in the chest, therefore our methods of positioning subjects should be improved, perhaps with a standard z-spacing used for all subjects. The same applies to the middle/side ratio, which also shows some correlation; however, its correlation with the amount of Fe_3O_4 is probably meaningless, because the correlation became lower with the more uniform group of non-smokers. The applied viscosity shows correlation with both Fe_3O_4 amount and density, which is believable because there could well be some sort of "clogging" viscosity with increased amounts of dust.

The relaxation shows a similar but lower correlation, again believable for the same reason. However, the lack of correlation between relaxation and amount of smoking is surprising, because this correlation in laboratory measurements was high; one explanation could be that the latter result was based on relaxation of dust recently inhaled, and perhaps the long residence time of Fe_3O_4 in our asbestos subjects had washed out the correlation. Another surprising result with relaxation is not shown in the table. The correlation between relaxation rate and the total dust index (74 subjects including welders) showed $r_s = 0.37$, which is significant at the 1% level. However, for the smokers within that group the correlation vanished, so that the first correlation is not believable, and could be only a random effect which is to be expected occasionally.

The data from Table III suggests, therefore, that the apparent viscosity and relaxation rate are worth pursuing further as auxiliary quantities in future measurements. The data also show that density of Fe_3O_4 in the lung generally yields a somewhat higher correlation in comparison to the amount of Fe_3O_4; this suggests that the density is a more useful quantity than the amount of Fe_3O_4 in the lung, and that this comparison should be pursued further as well.

REFERENCES

Becklake, M. R., Fournier-Massey, G., Rossiter, C. E., McDonald, J. C. (1972). Lung Function in Chrysotile Asbestos Mine and Mill Workers of Quebec. ARCH. ENVIRON. HEALTH 24, 401.

Cohen, D. (1973). Ferromagnetic Contamination in the Lungs and Other Organs of the Human Body. SCIENCE 180, 745.

Cohen, D. (1975). Measurements of the Magnetic Fields Produced by the Human Heart, Brain and Lungs. IEEE TRANS. MAG.-11, #2, 694.

Cohen, D. (1978). "Report of the Low-Fiend Group: The Magnetic Field of the Lung." Publication MIT/FBNML-78-1. National Technical Information Service, Springfield, Virginia.

Cohen, D., Arai, S. F., and Brain, J. D. (1979). Smoking Impairs Long-Term Dust Clearance from the Lung. SCIENCE 204, 514.

Freedman, A. P., Robinson, S. E., Goodman, L., et al (1979). Non-Invasive Magnetopneumographic Determination of Lung Dust Loads in Steel Arc Welders. CHEST 76, 352.

Freedman, A. P., Robinson, S. E., and Johnston, R. J. (1980). Non-Invasive Magnetopneumographic Estimation of Lung Dust Loads and Distribution in Bituminous Coal Workers. J. OCCUP. MED. 22, 613.

Gibbs, G. W. (1971). Qualitative aspects of dust exposure in the Quebec asbostos mining and milling industry. In "Inhaled Particles III." (W. H. Walton, Ed.), Vol. II, pp. 783-798, Unwin Brothers Ltd., Surrey, England.

Gibbs, G. W., and Lachance, M. (1972). Dust Exposure in the Chrysotile Asboestos Mines and Mills of Quebec. ARCH. ENVIRON. HEALTH 24, 189.

Kalliomaki, P. L., Korhonen, O., Vaaranen, V., et al (1976). Lung Retention and Clearance of Shipyard Arc Welders. INT. ARCH. OCCUP. ENVIRON. HEALTH 42, 83.

McDonald, J. C., Becklake, M. R., Fournier-Massey, G., and Rossiter, C. E. (1972). Respiratory Symptoms in Chrysotile Asbestos Mine and Mill Workers in Quebec. ARCH. ENVIRON. HEALTH 24, 358

Mosteller, F. and Tukey, W. (1977). "Data Analysis and Regression." Section 14H. Addison Wesley, Reading, Massachusetts.

Peress. L., Hoag, H., White, F., and Becklake, M. R. (1975). The Relationship between Closing Volume, Smoking, and Asbestos Dust Exposure. CLIN. RES. 23. 647A.

Rossiter, C. E., Bristol, L. J., Cartier, P. H., Gilson, J. G., Grainger, T. R., Sluis-Cremer, G. K., and McDonald, J. C. (1972). Radiographic Changes in Chrysotile Asbestos Mine and Mill Workers in Quebec. ARCH. ENVIRON. HEALTH 24, 388.

Snedecor, G. W., and Cochran, W. G. (1967). "Statistical Methods." 6th Edition, p. 194. Iowa State University Press, Ames, Iowa.

Suzuki, Y., and Churg, J. (1969). Structure and Development of the Asbestos Body. AM. J. PATH. 55, 79.

APPENDIX

The preceeding text, without this appendix, has been submitted for journal publication. The material in this appendix therefore is available only in this report. The material consists of details of methods (Appendix A) and of the results (Appendix B), and is intended for those who wish more knowledge of this work. However, Appendix A contains some details which are useful for magnetic measurements of the lung generally. The style of presentation in the appendix is occasionally more casual than in the main text.

APPENDIX A. SOME DETAILS OF METHODS

Performing the Magnetic Measurements

We first give a brief outline of the procedure we used during the first, 15-min visit of the subject to the magnetic station. We then present some details involved in this procedure.

Outline

1. The test is explained to the subject; the subject gives his I.D. and welding (torch cutting) history. Next the subject removes all his clothing except socks, and changes into athletic shorts furnished by us.
2. The chest thickness is measured, as well as the subject's chest height. Three points are marked on his chest on a horizontal line 10 cm above the ziphoid, and 10 cm apart. The height of the platform between coils is adjusted so that the subject's chest will be centered between the coils.
3. The subject is magnetized with a short pulse of 0.3 sec, of strength of about 400 gauss. Exact pulse length is noted on an oscilloscope.
4. Subject's chin and abdomen are checked for magnetic interferences by measurement with the flux gate gradiometer.
5. Guided by the operator, the subject undergoes his far-near-far motions, touching the shield for each "near" position. First the three chest points are measured, then the three back points.
6. The subject is magnetized for 30 sec at 750 gauss.
7. Again the gradiometer measurements are made for each of the chest and back points.
8. Step 7 is repeated approximately 20 min later, then again later if the subject's time permits.

Various Details

The MF-5000 gradiometer was arranged so the outer tips of the probes were 4 11/16 inches apart (hot-spots were 3 3/8 inches apart). The MF-5000 was always used on the 1 milligauss range; it fed a Varian recorder used on either a 10, 100, or 1,000 millivolt range. The chart speed was always 4 inches per minute. A calibrated coil was always present on the sensor closest to the subject, fed by the current from a calibration unit. It yielded either 1, 5, or 10, or 50 or 100 or 500 or 1,000 or 5,000 or 10,000 times 10^{-7} gauss, applied to one probe only. The capacity across the output of the MF-5000, which filtered out the higher frequencies, was 850 mf; this yielded a 3db point somewhere between 0.5 and 1.0 Hz, with a fall-off of 6db per octave, since filtering took place only at one point in the circuit; the chart recorder also had its own, slow time constant.

The two large magnetizing coils were set with an inside spacing of 12.0 inches, and were connected in series and fed by two storage batteries in series (24 v), yielding 750 gauss. When the switch was first closed, a current of about 400 amps flowed, which drooped during the 30-second application time to about 375 amps. During the 30-second magnetization, each subject was rocked from side to side slowly, in order to get fairly uniform magnetization across the entire chest; he was not moved up and down, however, or in and out, but placed about half-way, fore and aft. One subject was too heavy to fit between the magnets, and he was magnetized instead with a powerful Alnico magnet (about 250 gauss at the lung), slowly rubbed over his front and back.

Various difficulties were encountered during the measurements of the first few subjects; these included inability to exactly position the measuring points at the fluxgate, much magnetic contamination on the skin especially around the chin and neck, and the phenomenon we later called spiking. To cope with the first difficulty, we experimented with the subject's posture. During the first day or two, we asked the subject to "hang loose" while placing marks and making measurements. Subsequently, we found that this led to the trouble of back measurements, which were too low on the back; it was better to have the subject stand erect at all times, so that the back measurement lined up more on the upper part of the back, closer to the center of activity. Concerning the next problem, we began to vacuum the chest and often the back, certainly the neck, of each subject. We also tacked Kleenex to the subject's chest and back, in order to prevent magnetite in the air from clinging to his skin during magnetization. For spiking, we eventually found, by trial and error, that if we covered the front of the lucite shield with ordinary brown masking tape, the spiking disappeared. The spiking therefore is probably associated with some electrostatic discharge, at frequencies to which the fluxgate is sensitive. That is, skin rubbing against the lucite appears to generate charges in some fashion or other; this does not appear to be the case with skin against masking tape.

One phenomenon we noticed, as yet unexplained, was with subjects who had very high readings, such as some welders. It was noticed, when they stood at the "far" position, that we could see their breathing on the chart recorder. The amplitude of this modulation seemed to be far greater than one would expect at that distance. We should also note that, when a subject stood at the far position, with perhaps 10 or 12 inches between his skin and the lucite, the chart reading was not a true zero B_z; when a subject was asked to do a 180° turn at this far position, and we could see the modulation of the baseline accordingly, all readings should really be corrected upward by a certain percentage, because of the distance effect; that is, subjects were not adequately far away in their far positions. It appeared, on visual inspection, to be a correction of perhaps 3 or 5%. Another point, of some interest, is the modulation of the signal during breathing, by breathing, when the subject is at the lucite. It has been noticed that when the subject stands with his front pressing the lucite, there is almost no modulation by breathing; however, when his back is against the lucite, it is almost always seen that there is a large modulation of the signal.

For investigators using this technique for determining magnetic particles in the lung, the following list of interferences (both correctable and non-correctable) may be useful.

It is, of course, important that non-magnetic clothing be worn, and that shoes, belts, watches and false teeth be removed. In this study white athletic shorts with elastic waist bands were provided, although hospital trousers with drawstrings would have been preferable. Magnetic checks at neck height revealed steel pins in teeth; they also revealed a magnetic piece in a toupe! Abdominal checks showed up steel sutures from surgery, and often steel chips ingested with food. Steel items in the mouth and abdomen were often correctable by using a large but hand-held magnetic 60-Hz eraser. Steel particles embedded in the skin were occasionally erasable by a short-range eraser.

The sensitivity of the fluxgate gradiometer was limited by its rms noise of about $\sim 5 \times 10^{-7}$ gauss (rms$/\sqrt{\mathrm{Hz}}$). In addition to this intrinsic noise the field changes produced by passing cars and trucks would occasionally introduce a total reading uncertainty of up to 10×10^{-7} gauss. Assuming that they were random, this corresponds to an uncertainty in calculated total Fe_3O_4 from one reading of ± 0.3 mg of Fe_3O_4 or ± 0.1 mg for the average of 12 readings, because

$$\bar{\sigma} = \sigma / \sqrt{n}$$

where $\bar{\sigma}$ is the standard error between the sample mean and population mean,
σ is the standard deviation of a single measurement,
n is the number of trials (12 here).

For subjects having a magnetic lung burden so great that it exceeded the background noise by more than two orders of magnitude, it was found that difference in any two consecutive readings of the same point averaged about 9%. This variability is a function of how accurately the subject aligned the point on his body with the detector and on how hard he pressed against the plastic shield. These uncertainties are negligible compared to the $\pm$ 20% uncertainty which we believe was introduced by using an average chest thickness correction curve (Fig. 3(A)); they are also negligible compared to the $\pm$ 30% uncertainty in the I_{RS} value, which depends on the particle size and shape of the Fe_3O_4 in the lung. However, as noted in the text, this latter error is an absolute error, similar for all subjects, and does not affect the relative amount of Fe_3O_4 between subjects.

Processing the Magnetic Data

Obtaining the Amount of Fe_3O_4 in the Lung from Measurements of the Remanent Field

In order to convert gradiometer readings into amount of magnetite in the lungs, two factors must be used. The first is the remanent magnetic moment of the Fe_3O_4 particles in the lung following magnetization in the coils. It will be shown that this value depends on the grain size, aspect ratio, and orientation of the magnetic particles. The second is a factor to account for the distance between the lungs and the detector (which varies with the individual subject's chest thickness, lung thickness and shape) and for the magnetic particle extended distribution within the lungs.

1. The Magnetic Moment

The remanent magnetization of dispersed magnetite powders has been measured by Parry (Parry, 1965) who obtained good agreement compared to the theory (Stacey and Banerjee, 1974). The theory uses

$$I_{RS} = H_c / N \qquad (1)$$

where I_{RS} is the remanent magnetization in emu/cc,

H_c is the coercive force in oersteds, and

N is the effective self-demagnetizing factor for the grains (For spherical grains $N = 4\pi/3$).

Experimentally Parry found that for a 1% dispersion

$$I_{RS} = 3.0 \times 10^{-3} H_c \qquad (2)$$

which means (using a factor of 100) that the value of N is 3.32, i.e., 0.79 times that of a spherical grain. This means that some of the grains were elongated and aligned in the direction of the applied field.

Another useful relationship is that $H_c \propto d^{-n}$ (3) where d is the grain diameter; this is to indicate that H_c (hence I_{RS}) indeed depends on particle size of the dust inhaled. Measurement for different materials by several authors have given values of n in the range $0.25 \leq n \leq 1$.

The lung is well known to exclude particles exceeding about five microns in diameter from deposition in the alveoli. Thus the range of unannealed grain diameters with which we can deal lies between 1.5 and 5 microns, having corresponding H_c's between 250 and 100 Oe (from eqn. (1)). The lower limit is only set by Parry's range, although smaller particles exist in the alveoli; the upper limit is set by the alveoli. Some recent work, however, extends the lower limit (Dunlop, 1972).

In this Quebec study we assumed that the magnetite particles in the lung had the same remanent magnetization as the "ferric-ferrous oxide, block, purified" obtained from Fisher Scientific (I-119 # 74192). These particles were of $\approx$ 2 micron mean diameter. We calibrated these by mixing

5 mg into 2 cc of an epoxy (EZ Mount plastic, Donsel Equipment Co., Westboro, MA) in a clear plastic cubical box 2 cm on a side. Pairs of samples differed by the magnetic field environment in which they were placed while the epoxy hardened; unoriented samples were placed in a magnetic shield, while oriented samples were placed in a field of ~ 700 gauss.

We then measured the remanent field of the samples using a fluxgate probe (MF-500,* manufactured by Automation Industries) in the MIT shielded room. A single probe was used in these experiments (the second probe of this gradiometer was placed in a separate shield).

The procedure before measuring each sample was to first demagnetize it in a 60-Hz demagnetizer, then magnetize it in a 750-gauss field for 30 seconds. The remanent magnetization was calculated from the formula for the field from a magnetic dipole

$$B_z = \frac{2\, I_{RS}\, V}{z^3} = \frac{2\, I_{RS}\, m}{z^3\, \rho} \qquad (4)$$

where m is the mass of magnetite in grams,

I_{RS} is the remanent magnetization in emu/cc (and is therefore of of different dimensions than the I used in the text),

z is the distance between the center of the dipole and the detector in cm,

ρ is the density of Fe_3O_4 in grams/cc,

B_z is the axial magnetic field in gauss.

Typical values for an unoriented sample were $m = 4.8$ mg, $z = 12.7$ cm, $\rho = 5.2$ gm/cm^3, $B_z = 35 \times 10^{-6}$ gauss; this gives $I_{RS} = 38.9$ emu/cc or 7.5 emu/gm. Since the saturation magnetization of magnetite, I_S, is 450 emu/cc, $I_{RS}/I_S = 0.086$.

An independent calculation of I_{RS}/I_S was obtained by measuring the coercive force H_c for an unoriented sample in a PAR Vibrating Sample Magnetometer Model CC-1. Here an H_c of 150 Oe was measured. Using eqn. (1) with $N = 4\pi/3$, this gives $I_{RS}/I_S = 0.080$, in good agreement with the direct measurement.

For the samples which were oriented in the 700-gauss field while the plastic hardened, the measured value of I_{RS} was 64.5 emu/cc, or 12.4 emu/gm,

---

*No longer manufactured by them. The basic design is by the Förster Co. of West Germany, and their units <u>are</u> available.

which is 70% greater than for the unoriented particles, or $I_{RS} / I_S = 0.143$. The increase is due to the decreased demagnetizing factor N for particles with their longer axes aligned in the direction of the applied field. Since it is assumed that at least some of the Fe_3O_4 particles in the lungs rotate during the time the field is applied, a value of I_{RS} of 10 emu/gm (or 52 emu/cc) is used in this study, since it lies between the unoriented and completely aligned values.

2. The Spatial Factor: The Extended Lung vs. the Dipole

For the actual extended lung, we can assume that its z-dependence can be approximated as that magnetic dipole (z^{-3}) for distances greater than 20 cm between the center of the lung and the detector. For distances less than 20 cm it is found that the B_z for the human lung falls off less rapidly than z^{-3}. This falloff distance factor, $F_m(z)$, is plotted as the lower curve in Fig. 3(A); (the sub-m refers to a magnetometer or single-probe measurement, as opposed to a gradiometer, the latter designated as sub-g; we also note that in the tables $F_g(z)$ is used as $F_g(d)$, as they are meant to be interchangeable here). This curve is an average of two experimentally determined curves, one for a tall and thin subject, the other for a short and stocky subject. $F_m(z)$ is defined as

$$F_m(z) = \frac{B_m(z)}{2\,M_r}, \text{ or } B_m(z) = 2\,M_r\,F_m(z) \tag{5}$$

where M_r is the total remanent magnetic moment.

The net reading for the gradiometer used in this study is the difference between two probes whose sensing elements were 8.6 cm apart. Thus the gradiometer distance factor, $F_g(z)$, is defined in terms of the magnetometer distance factors, $F_m(z)$ as

$$F_g(z) = F_m(z) - F_m(z + 8.6), \text{ and} \tag{6}$$

$$B_g(z) = 2\,M_r\,F_g(z) = 2\,I_{RS}\,m\,F_g(z)\,/\,\rho \tag{7}$$

where $B_g(z)$ is the average gradiometer field reading in units of 10^{-7} gauss, or

$$B_g(z) = 1/6 \sum_{t=0} 6 \tag{8}$$

where $\sum_{t=0} 6$ is the sum of the six gradiometer readings taken at the six lung points; these are three on the chest, three on the back, each extrapolated back to time zero, which is just at the end of the magnetization in the coils. Combining eqns. (7) and (8) and solving for m gives

$$m\ (\text{mg of } Fe_3O_4) = [83.3\ \rho \sum_{t=0} 6]\ 10^{-3}\ /\ [F_g(z)\ I_{RS}] \tag{9}$$

and since $I_{RS} = 52$ emu/cc and $\rho = 5.2$ gm/cc, then

$$m\ (\text{mg of } Fe_3O_4) = [8.33 \sum_{t=0} 6]\ 10^{-3}\ /\ F_g(z) \tag{10}$$

or since the average lung volume, V_ℓ, is equal to FRC + TV/2,

the density $$m\ /\ V_\ell = [8.33 \sum_{t=0} 6]\ 10^{-3}\ /\ \{F_g(z)\ [FRC + TV/2]\}. \tag{11}$$

References

Dunlop, D. J. (1972). Magnetite: Behavior near the Single Domain Threshold. *Science* 176, 41.

Parry, L. G. (1965). Magnetic Properties of Dispersed Magnetite Powders. *Phil. Mag.* 11, 303.

Stacey, F. D., and Banerjee, S. K. (1974). "The Physical Principles of Rock Magnetism." Elsevier Scientific Pub. Co., New York.

APPENDIX B. SOME DETAILS OF RESULTS

In this part of the Appendix two types of details are presented of the results of measurements. The first type consists of data of each of the 115 individuals. The second type consists of bar graphs which illustrate the distribution of quantities within the group. The individual data is given in the following Table BI. We here explain the column headings of that table.

SUBJECT NO.: This is the subject number, only for purposes of this table. We are following the rule of preserving the subject's anonymity.

AGE: This was the subject's age at the time of the study, in 1974. For purposes of the lung function tests for which this group was chosen, the ages were confined to the ranges 25-35 and 41-50. In addition, three individuals were measured magnetically whose ages are not shown (#3, 5, 97), but who are over 50; there were no dust indices and other data available for them, hence they were not included in the main correlations.

HEIGHT: Included only as information on the body build of the subject.

WEIGHT: Included only as information on the body build of the subject.

CHEST TH: This is the chest thickness, used to calculate the distance from the lung center to the nearer probe, for application to Fig. 3(A) of the text. The distance used (d) was (half the chest thickness) + 1.5 cm. Thickness is here given in inches (not uncommon in 1974!)

LUNG VOL(ℓ): This is the lung volume (in liters), used for calculating the density of Fe_3O_4 in the lung (further on). We calculated this volume by multiplying the FRC (measured by the McGill Group during the clinic visit) by 1.08, which is an approximate way to include 0.5 of the tidal volume.

V.CAP: The vital capacity, also measured by the McGill group during the clinic visit, expressed as % of predicted value; because the subjects were chosen to be without pulmonary abnormality, the range of values is restricted accordingly.

CIGS/DAY: The number of cigarettes smoked per day, up to the time of the study. Ex-smokers are indicated by ( ); in our correlations, we included these with the smokers. The values in this column were determined by careful questioning by the McGill group.

YRS WELD.: The years of welding exposure, as defined in the text (METHODS). The designation < 0.2 indicates that, as far as we can determine, the subject had some welding exposure, but certainly less than 0.2 years. A bar under a value indicates that the welding exposure was recent, as opposed to "old"; recent was defined as greater than 0.10 of his peak yearly exposure was obtained during the past year (ending in Aug. '74).

DUST: This is the total dust exposure index in units of (millions of particles/cu ft) x yrs. As explained in the text, it is based on midget impinger counts, etc., and only applied up to the end of 1966. There was no inclusion for dust exposure after that; however, for the period not included, the dust levels were generally much lower than previously.

$\Sigma 6(10^{-7}g)$: This is the sum of the B_z values measured over the six lung locations on the torso; it is 6 x (the average remanent field from the lung). It is used in the formula (see METHODS) to yield the amount of Fe_3O_4. A designation such as $40 \rightarrow 75$ indicates that the "true value" can be anywhere in that range, i.e., the error is greater than normal.

CONV.($F_g(d)$): This is the geometric conversion factor involving both the extended lung and the gradiometer (differences), as explained in METHODS (both in the text and in App. A).

AMT.Fe_3O_4: (REVISED) After the data was processed and prepared, it was seen that $F_g(d)$ should have been revised downward by about 13%, with variations among individuals; hence, the amt. Fe_3O_4 should have been revised upward by a corresponding amount. This new, revised value was not used as data in the text. For future use, it is a better value than the unrevised value.

AMT.Fe_3O_4: (UNREV.) This is the unrevised value, actually used in the text for the measured amount of Fe_3O_4 in the lungs of a worker.

DENS.: This is the density of Fe_3O_4 in the lung, calculated by dividing the revised amount of Fe_3O_4 by the lung volume.

MIDDLE/SIDE: This is information re distribution of Fe_3O_4 in the lung. It is the middle B_z, summed front and back, divided by the sum (front and back) of the left side, and the right side. It is otherwise written as $2\Sigma M/\Sigma L+\Sigma R$.

LEFT/RIGHT: This is also the distribution within the lung and is the two left points divided by the two right points, otherwise written as $\Sigma L/\Sigma R$.

APP.VISC.: This is the apparent viscosity, defined as $\Sigma 6$ from the long pulse, divided by $\Sigma 6$ from the short pulse. Numbers with ( ) indicate larger errors than usual.

RELAXATION: This is relaxation group into which this subject fits. A minus after the group refers to the lower range within that group, a plus refers to the higher range within that group, and no sign refers to the middle of the group. It is a finer designation than just the course grouping given in the text RESULTS. The ( ) refers to a larger error than usual, perhaps by a half-group; e.g. (III) could mean III- or III+.

TABLE BI. DATA OF EACH SUBJECT

SUBJECT NO.	AGE	HEIGHT(cm)	WEIGHT(kg)	CHEST T(in)	LUNG VOL(ℓ)	V.CAP(%pr)	CIGS/DAY	YRS WELD.	DUST(mpy/cf)	$\Sigma б(10^{-7}g)$	CONV. $(F_g(d))$	AMT. Fe_3O_4(mg) (REVISED)	AMT. Fe_3O_4(mg) (UNREV.)	DENS. (μgm/cc)	MIDDLE/SIDE	FRONT/BACK	LEFT/RIGHT	APP. VISC.	RELAXATION
1	49	160	71	10.4	1.8	87	0	<0.1	26	0→65	1.63	<0.4	<0.3	0.0	-	-	-	-	-
2	49	170	75	10.6	4.1	94	20	<0.1	107	665	1.56	3.6	3.0	0.9	0.3	0.8	1.0	2.8	II-
3	-	173	71	9.8	-	-	20	0	-	1140	1.80	5.3	4.2	-	0.3	1.7	1.1	1.8	II+
4	49	155	57	9.2	2.1	78	20	0	589	590	1.97	2.5	1.9	1.2	0.4	1.0	0.8	2.2	II
5	-	167	64	9.5	-	-	20	0	-	380	1.88	1.7	1.3	-	0.3	0.8	1.3	1.9	II+
6	28	174	63	9.4	5.0	116	0	<0.1	1	360	1.93	1.6	1.2	0.3	0.3	1.1	0.9	-	II+
7	43	173	71	9.6	2.7	-	20	1.2	116	5610	1.85	25.3	20.0	9.4	0.4	0.9	0.8	1.3	II
8	49	162	64	9.6	2.4	88	50	0	5	40→75	1.85	0.2	0.2	00.9	0.4	-	-	-	-
9	44	172	83	10.9	4.1	130	(20)	0	10	480	1.50	2.7	2.3	0.7	0.3	0.7	0.7	2.6	II-
10	50	168	71	9.8	2.9	114	0	<0.1	54	2050	1.80	9.5	7.6	3.3	0.4	0.8	0.8	-	I+
11	43	167	75	9.6	-	104	0	<0.2	45	1450	1.85	6.5	5.2	-	0.3	0.9	1.0	2.3	II
12	50	174	89	11.2	2.6	111	20	0	111	0→70	1.43	<0.5	<0.4	0.0	-	-	1.0	-	-
13	47	175	75	9.8	3.8	112	0	0	588	2710	1.81	12.5	10.0	3.3	0.2	0.6	1.0	1.9	III
14	49	166	90	12.0	1.7	87	(8)	0	665	285	1.23	1.9	1.7	1.1	0.5	0.6	0.7	2.4	II
15	47	176	88	10.0	2.9	93	(25)	0	407	125	1.74	0.6	0.5	0.2	0.4	0.9	0.9	(2.9)	(III)
16	48	162	57	9.0	3.2	120	22	0	618	145	2.05	0.6	0.5	0.2	0.3	0.5	0.8	1.8	(I+)
17	50	167	61	8.8	2.7	96	20	4.0	525	2800	2.10	11.1	8.5	4.1	0.3	0.9	0.8	1.8	II
18	50	172	70	9.8	2.9	92	20	0	106	265	1.80	1.2	1.0	0.4	0.3	0.7	2.0	1.55	(II)
19	46	167	60	8.9	2.9	114	0	0	29	550	2.07	2.2	1.7	0.8	0.3	0.9	0.9	-	II-
20	49	161	58	9.2	3.7	-	0	2.2	30	1300	1.97	5.5	4.3	1.5	0.4	1.4	0.9	2.6	III-
21	31	165	76	10.0	2.2	112	0	0	2	145	1.74	0.7	0.6	0.3	0.3	1.9	0.9	-	(IV)
22	48	167	62	9.0	3.5	97	22	3.2	692	1210	2.05	4.9	3.8	1.4	0.3	1.1	0.9	1.6	III-
23	28	178	84	9.8	2.9	119	0	<0.1	40	335	1.80	1.6	1.2	0.6	0.3	0.6	1.0	2.5	(I)

TABLE BI. DATA OF EACH SUBJECT (CON'T.)

SUBJECT NO.	AGE	HEIGHT(cm)	WEIGHT(kg)	CHEST T(in)	LUNG VOL(ℓ)	V.CAP(%pr)	CIGS/DAY	YRS WELD.	DUST(mpy/cf)	Σ6 (10^{-7}g)	CONV.(F_g(d))	AMT.Fe_3O_4(mg) (REVISED)	AMT.Fe_3O_4(mg) (UNREV.)	DENS.(μgm/cc)	MIDDLE/SIDE	FRONT/BACK	LEFT/RIGHT	APP.VISC.	RELAXATION
24	50	163	86	9.8	2.1	83	0	0	187	0→65	1.80	<0.2	<0.2	0.0	-	-	-	-	-
25	42	164	68	9.6	2.4	104	(10)	0	9	0→70	1.85	<0.2	<0.2	0.0	-	-	-	-	-
26	47	179	96	11.4	1.6	110	0	< 0.1	442	8430	1.37	51.3	45.0	2.0	0.4	0.7	0.9	2.9	III
27	31	173	82	10.0	3.2	109	15	0	1	0→70	1.74	<0.4	<0.3	0.0	-	-	-	-	-
28	43	178	66	9.0	4.1	103	15	3.0	123	630	2.05	2.6	2.0	0.6	0.3	1.3	1.0	1.5	II
29	47	165	60	9.0	2.9	-	18	1.2	117	675	2.05	2.7	2.1	0.9	0.2	1.3	0.7	-	II-
30	45	173	80	10.2	2.7	116	12	2.6	124	800	1.66	4.0	3.3	1.5	0.2	0.8	1.2	1.9	III-
31	34	171	70	10.2	3.0	98	15	2.9	20	2570	1.66	12.9	11.0	4.3	0.4	0.7	0.7	2.0	I
32	49	187	80	10.6	5.2	89	18	0.5	17	1310	1.56	7.0	5.9	1.3	0.3	1.0	1.1	2.0	II-
33	28	171	77	9.4	3.7	120	0	1.0	1	2140	1.93	9.2	7.3	2.5	0.4	0.9	1.0	2.5	II+
34	31	189	82	9.5	4.0	112	0	< 0.1	3	85→95	1.88	0.4	0.3	0.1	0.1	-	1.0	(1.5)	-
35	48	186	92	11.4	3.2	133	35	0	22	0→105	1.37	<0.7	<0.6	0.0	-	-	-	-	-
36	45	174	74	10.5	2.6	98	25	0	125	140	1.60	0.7	0.6	0.3	0.4	0.8	0.9	-	-
37	44	167	67	9.2	4.4	106	0	0	214	350	1.97	1.5	1.2	0.3	0.3	0.9	0.6	1.9	II
38	26	181	75	10.0	4.5	109	(10)	<0.7	23	1190	1.74	5.7	4.6	1.3	0.3	0.8	1.0	1.7	II+
39	47	163	66	10.5	2.7	92	18	0.8	579	1250	1.60	6.5	5.4	2.4	0.4	0.7	1.4	2.8	III-
40	43	179	74	9.2	3.8	109	9	18.0	10	12300	1.97	52.0	40.0	14.0	0.2	0.8	0.7	1.3	III+
41	27	169	88	10.5	3.0	115	0	0	2	0→70	1.60	<0.4	<0.3	0.0	-	-	-	-	-
42	31	172	80	10.5	3.0	114	15	0.3	21	425	1.60	2.2	1.8	0.7	0.5	1.2	0.8	1.3	II-
43	48	177	84	11.0	2.4	101	0	0.4	507	240	1.46	1.4	1.2	0.6	0.3	1.1	0.6	(2.2)	(III)
44	46	177	73	9.4	2.8	102	0	18.0	73	7020	1.93	30.3	24.0	11.0	0.2	1.2	1.1	2.6	III+
45	48	161	87	11.2	2.8	118	40	0.2	133	460	1.43	2.7	2.3	1.0	0.3	0.7	0.8	1.4	II+
46	41	172	82	10.6	2.7	91	30	< 0.1	18	35→80	1.56	0.2	0.3	0.8	-	-	1.0	-	-

TABLE BI. DATA OF EACH SUBJECT (CON'T.)

SUBJECT NO.	AGE	HEIGHT(cm)	WEIGHT(kg)	CHEST T(in)	LUNG VOL(ℓ)	V.CAP(%pr)	CIGS/DAY	YRS WELD.	DUST(mpy/cf)	$\Sigma\delta(10^{-7}g)$	CONV. $(F_g(d))$	AMT.Fe_3O_4(mg) (REVISED)	AMT. Fe_3O_4 (UNREV.)	DENS.(μgm/cc)	MIDDLE/SIDE	FRONT/BACK	LEFT/RIGHT	APP.VISC.	RELAXATION
47	41	172	70	9.6	3.8	127	15	15.0	11	9530	1.85	42.9	34.0	11.0	0.2	1.4	1.0	2.8	II
48	44	175	73	10.2	4.8	95	25	< 0.1	9	170	1.66	0.8	0.7	0.2	0.3	1.1	0.7	(1.5)	-
49	50	173	89	10.5	1.9	115	0	2.1	30	455	1.60	2.4	2.0	1.3	0.5	1.1	1.1	-	(III)
50	50	174	89	11.4	-	-	(50)	0	835	1160	1.37	7.0	6.2	-	0.3	-	1.1	1.6	III
51	49	155	49	8.0	2.2	51	(12)	0	534	525	2.35	1.9	1.3	0.9	0.3	1.1	0.6	2.1	III
52	46	173	75	9.5	2.8	103	20	0	21	560	1.88	2.5	2.0	0.9	0.5	0.8	1.1	2.4	(II)
53	47	166	60	9.5	3.3	127	15	0	11	0→70	1.88	<0.2	<0.2	0.0	-	-	-	-	-
54	44	175	78	10.5	3.5	80	0	0	227	570	1.60	3.0	2.5	0.9	0.4	0.8	0.8	-	II
55	50	175	77	11.2	3.2	113	0	0	72	450	1.43	2.6	2.3	0.8	0.4	0.9	0.8	2.0	II
56	27	180	94	10.8	3.0	104	0	1.3	32	630	1.51	3.5	2.9	1.2	0.3	0.8	0.9	2.3	I+
57	46	178	74	9.0	3.2	85	20	0	116	130	2.05	0.5	0.4	0.2	0.2	1.2	0.9	-	-
58	45	167	70	11.2	2.5	101	0	0	7	35→65	1.43	0.2	0.2	0.1	-	-	-	-	-
59	43	172	67	9.6	3.6	144	0	0	7	0→70	1.85	< 0.2	< 0.2	0.0	-	-	-	-	-
60	43	171	77	10.2	2.6	105	(50)	< 0.1	57	150	1.66	0.8	0.6	0.3	0.5	0.9	1.2	(1.6)	-
61	46	168	66	9.0	2.6	87	38	0	110	285	2.05	1.2	0.9	0.5	0.4	1.1	1.1	1.1	III
62	43	172	73	9.5	2.4	99	20	1.2	13	150	1.88	0.7	0.5	0.3	0.4	0.9	1.0	-	-
63	46	170	65	9.0	2.9	88	0	0	154	230	2.05	0.9	0.7	0.3	0.4	0.8	0.9	-	-
64	49	176	61	9.5	4.1	96	25	0	641	1140	1.88	5.0	4.0	1.2	0.5	1.1	1.0	2.7	II
65	43	178	63	8.2	3.9	94	55	0	8	245	2.30	0.9	0.6	0.2	0.2	1.0	1.4	(4.0)	I+
66	46	162	79	10.0	2.5	106	0	1.5	523	2900	1.74	13.9	11.0	5.6	0.3	1.1	1.6	2.1	III
67	44	159	64	10.0	2.6	98	(25)	0	308	1400	1.74	6.7	5.4	2.6	0.4	0.8	0.8	-	II+
68	48	163	89	12.0	3.0	-	12	0.8	119	430	1.23	2.9	2.6	1.0	0.3	0.6	0.9	(2.7)	II+
69	50	177	87	11.2	2.7	80	25	0.8	644	1200	1.43	7.0	6.1	2.6	0.3	0.6	0.7	2.6	II+

TABLE BI. DATA OF EACH SUBJECT (CON'T.)

SUBJECT NO.	AGE	HEIGHT(cm)	WEIGHT(kg)	CHEST T(in)	LUNG VOL(l)	V.CAP(%pr)	CIGS/DAY	YRS WELD.	DUST(mpy/cf)	Σ6(10^{-7}g)	CONV.(F_g(d))	AMT.Fe_3O_4(mg) (REVISED)	AMT.Fe_3O_4 (UNREV.)	DENS.(μgm/cc)	MIDDLE/SIDE	FRONT/BACK	LEFT/RIGHT	APP.VISC.	RELAXATION
70	34	165	53	8.0	2.9	88	18	0	1	325	2.35	1.2	0.8	0.4	0.3	0.8	0.9	-	(II)
71	48	170	61	10.0	3.6	92	30	0	540	20→75	1.74	0.1	0.2	0.0	-	-	-	-	-
72	43	181	75	9.2	3.7	91	25	5.3	8	1230	1.97	5.2	4.0	1.4	0.3	0.7	0.9	1.7	II+
73	28	176	77	10.0	3.8	117	10	0.4	0	370	1.74	1.8	1.4	0.5	0.4	0.8	0.9	1.7	(I+)
74	48	168	66	9.5	3.0	84	25	0	20	225	1.88	1.0	0.8	0.3	0.3	0.6	0.9	-	-
75	45	164	71	9.0	1.9	95	18	1.9	3	135→150	2.05	0.5	0.4	0.3	0.3	-	-	(2.2)	-
76	42	174	69	9.4	3.0	126	0	0.4	20	2390	1.90	10.5	8.2	3.5	0.3	1.1	1.2	2.0	II+
77	31	178	60	8.4	4.0	104	18	0	0	45→70	2.22	0.2	0.1	0.1	-	-	1.0	-	-
78	46	161	89	10.9	1.5	65	40	0.6	595	1490	1.50	8.3	7.0	5.5	0.3	0.6	1.7	1.8	II+
79	49	161	73	11.0	1.5	88	0	0	241	170	1.46	1.0	0.8	0.7	0.4	0.5	0.7	-	(III)
80	41	175	69	10.2	2.6	108	0	<0.1	89	200	1.66	1.0	0.8	0.4	0.4	0.6	0.7	(2.1)	(II+)
81	49	175	63	9.4	3.2	110	25	0	10	65→75	1.90	0.3	0.2	0.1	-	-	0.8	-	-
82	29	178	72	9.0	2.9	104	20	1.2	0	430	2.05	1.7	1.4	0.6	0.2	0.9	0.9	2.1	II-
83	35	173	75	10.6	1.9	105	20	0.2	58	910	1.56	4.8	4.1	2.5	0.4	1.2	1.3	1.7	II+
84	43	172	66	10.2	5.2	140	0	0	228	1910	1.66	9.6	7.9	1.8	0.2	0.9	1.1	3.1	II+
85	27	164	75	10.0	1.7	97	15	0.5	20	785	1.74	3.8	3.1	2.2	0.3	0.9	1.1	1.9	II-
86	45	166	85	11.5	4.0	129	50	0	126	155	1.35	1.0	0.9	0.3	0.3	1.2	0.7	-	-
87	26	172	65	9.0	5.0	119	0	0.5	41	225	2.05	0.9	0.7	0.2	0.4	1.2	0.8	-	II+
88	32	169	56	8.0	3.9	84	0	0	26	0→70	2.35	<0.2	<0.2	0.0	-	-	1.0	-	-
89	27	176	56	8.0	2.9	89	20	0	0	820	2.35	2.9	2.1	1.0	-	0.6	0.6	1.7	II
90	41	164	54	8.4	2.6	81	0	29.0	45	51800	2.22	194.0	140.0	75.0	0.5	0.9	1.2	3.0	III+
91	31	176	113	12.0	1.9	89	25	0.9	1	230	1.23	1.6	1.4	0.8	0.4	0.5	0.7	(1.8)	-
92	46	175	84	11.0	3.3	99	28	0	129	1490	1.46	8.5	7.3	2.6	0.2	0.6	0.9	1.7	II

TABLE BI. DATA OF EACH SUBJECT (CON'T.)

SUBJECT NO.	AGE	HEIGHT(cm)	WEIGHT(kg)	CHEST T(in)	LUNG VOL(ℓ)	V.CAP(%pr)	CIGS/DAY	YRS WELD.	DUST(mpy/cf)	$\Sigma 6 (10^{-7} g)$	CONV. (F_g(d))	AMT. Fe_3O_4(mg) (REVISED)	AMT. Fe_3O_4(mg) (UNREV.)	DENS. (μgm/cc)	MIDDLE/SIDE	FRONT/BACK	LEFT/RIGHT	APP.VISC.	RELAXATION
93	31	179	75	9.5	2.9	125	0	<0.1	2	125	1.88	0.6	0.4	0.2	0.4	0.6	0.9	-	-
94	29	178	68	9.0	3.7	111	25	1.1	0	760	2.05	3.1	2.4	0.8	0.3	0.8	0.7	1.8	II-
95	27	174	107	12.0	2.8	104	23	0	0	0→80	1.23	0	<0.5	0.0	0.9	-	-	(1.3)	-
96	28	173	96	11.0	2.2	95	0	<0.1	23	0→150	1.46	<0.9	<0.8	0.0	-	-	-	-	-
97	-	175	87	11.5	-	-	28	1.0	-	325	1.35	2.0	1.8	-	0.4	0.8	0.9	1.0	IV
98	34	180	84	10.6	3.3	99	255	<0.1	30	0→70	1.56	<0.4	<0.3	0.0	-	-	-	-	-
99	43	171	69	10.2	4.4	144	10	2.8	19	1600	1.66	8.0	6.6	1.8	0.3	1.0	0.8	2.8	I
100	34	178	100	11.6	2.8	106	4	0.2	1	230	1.33	1.4	1.3	0.5	0.3	0.6	1.1	1.9	(II)
101	29	172	60	10.0	3.0	117	0	0	22	85→110	1.74	0.4	0.3	0.1	0.4	-	-	-	-
102	27	180	65	8.9	4.5	103	10	0.2	1	1120	2.09	4.5	3.4	1.0	0.3	0.9	1.2	2.0	I+
103	49	169	78	10.2	2.7	90	0	0.8	267	1070	1.66	5.4	4.4	2.0	0.3	0.7	0.4	1.9	III+
104	29	171	91	10.5	2.3	77	(20)	<0.1	32	55→75	1.60	0.3	0.2	0.1	-	-	-	-	-
105	27	175	92	11.2	2.1	91	0	0	2	0→70	1.43	<0.5	<0.4	0.0	-	-	-	-	-
106	45	165	69	10.2	2.6	-	20	0	137	210	1.66	1.0	0.9	0.4	0.4	0.6	1.0	(3.9)	-
107	49	166	85	11.0	1.9	100	0	<0.1	378	1050	1.46	6.0	5.1	3.2	0.2	0.8	1.0	2.9	IV-
108	47	162	67	10.2	2.9	90	20	0.4	113	1040	1.66	5.2	4.3	1.8	0.4	1.0	0.9	2.0	II-
109	26	172	61	9.6	3.8	119	0	0	2	0→70	1.85	<0.3	<0.2	0.0	-	-	-	-	-
110	48	183	83	10.2	3.1	97	20	2.0	822	230	1.66	1.2	0.9	0.4	0.3	0.9	0.6	1.6	-
111	29	173	83	10.0	3.9	117	0	0	1	240	1.74	1.1	0.9	0.3	0.4	0.7	0.9	-	(II-)
112	49	174	83	11.0	2.7	97	(25)	5.0	125	2500	1.46	14.3	12.0	5.3	0.4	0.8	1.0	2.2	II+
113	49	175	74	9.5	3.9	92	25	0	596	190	1.88	0.8	0.7	0.2	0.4	1.3	0.9	1.6	II+
114	49	173	175	14.2	-	75	0	<0.1	202	0→245	0.84	<2.8	<2.4	-	-	-	-	-	-
115	41	167	68	8.9	2.6	87	18	0	7	150→160	2.09	0.6	0.5	0.2	0.4	1.1	1.0	-	(III)

The following six figures are visual displays of the distribution data presented in Table II in the text. Our purpose is to clarify these quantities.

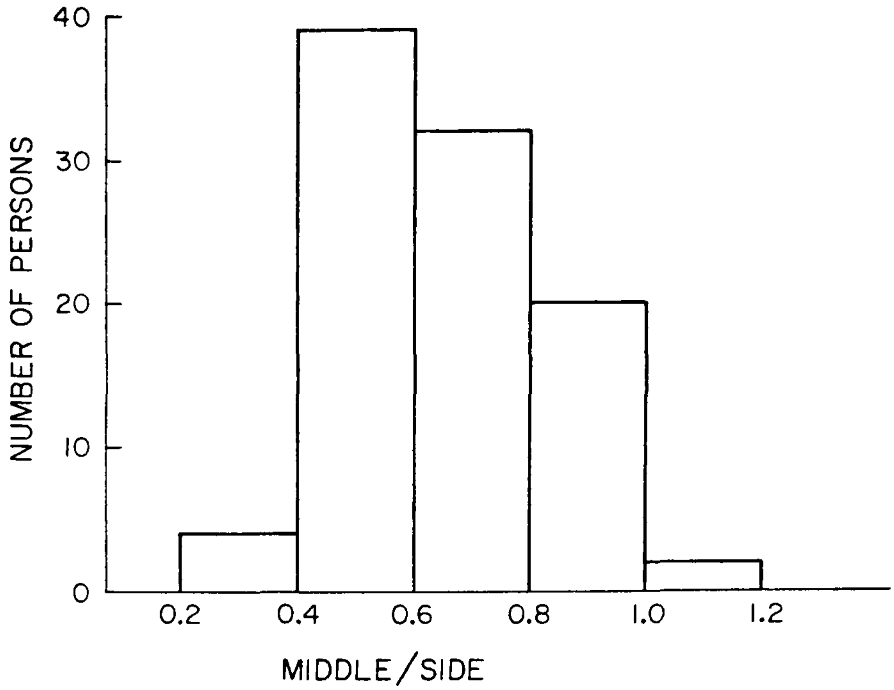

Fig. B1. Distribution of the ratio of the remanent field at the middle of the torso to that on the average of both sides, for all workers who had enough Fe_3O_4 to yield a ratio. The sum of front and back is used for right, middle and left.

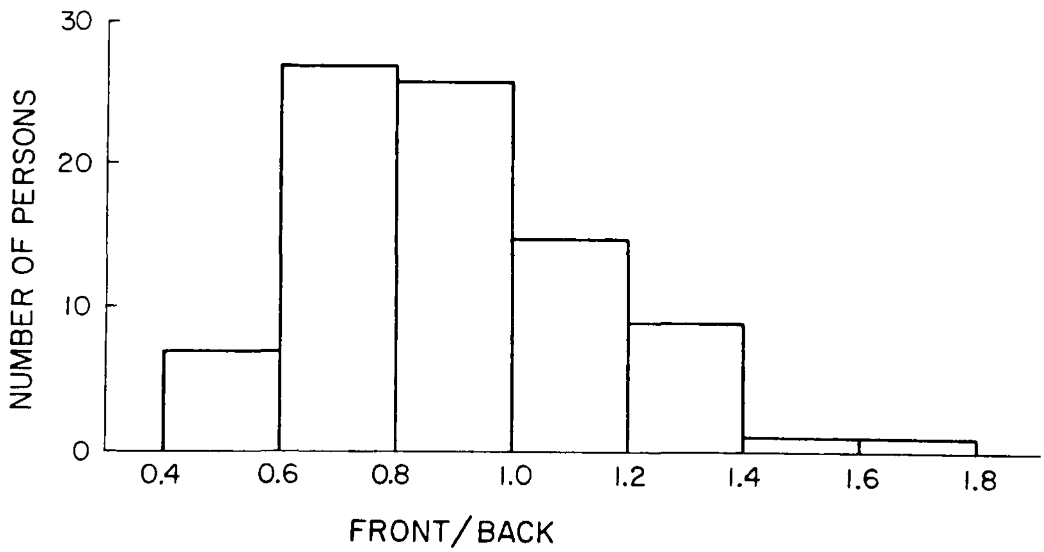

Fig. B2. Distribution of the ratio of the remanent field at the front of the torso to that at the back. The sum of the right, middle, and left is used. The spread is quite large here because of the coarse z-spacing used, front and back. The spread would presumably narrow if a constant z-spacing was used for all subjects, as suggested by the correlation in Table III in the text.

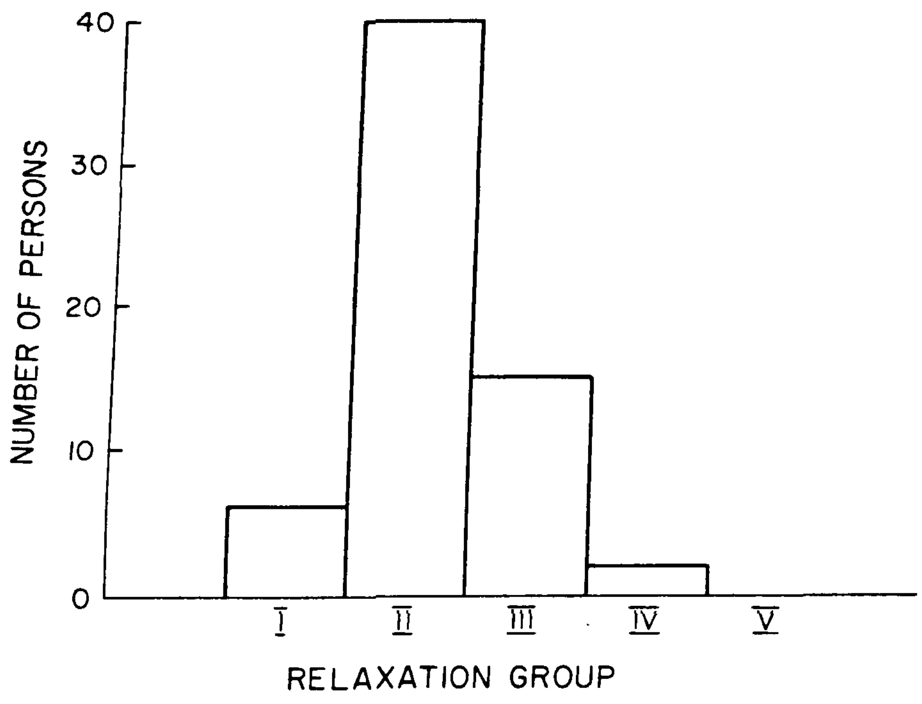

Fig. B3. Distribution of the relaxation rate for all workers who had enough Fe_3O_4 to yield a crude relaxation curve. The groups correspond to those of Fig. 3 in the text.

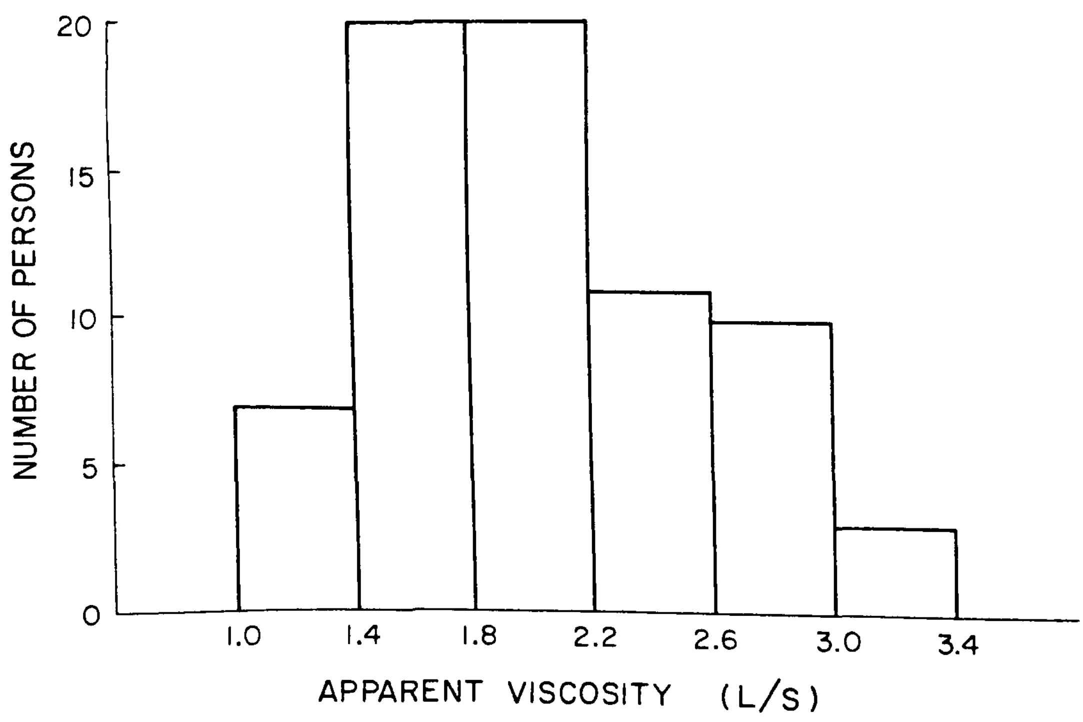

Fig. B4. Distribution of the apparent viscosity for all workers where there was enough Fe_3O_4 to yield the ratio of remanent field from the long pulse to that of the short pulse.

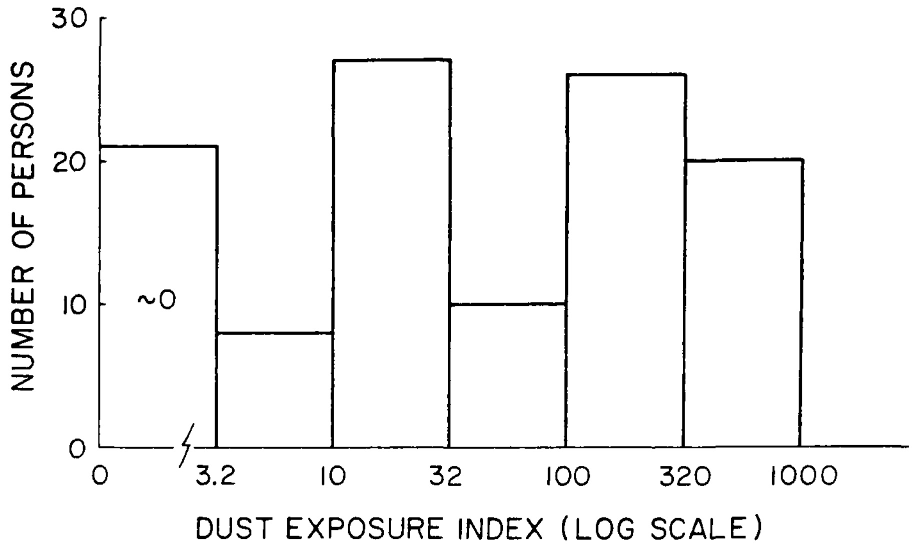

Fig. B5. Distribution of total dust exposure index. Welders are included here. (Three workers were measured who had no indices.) A log scale is used, except at the first interval, which goes down to zero. The workers in this interval, mostly office workers, therefore have relatively low indices (~0).

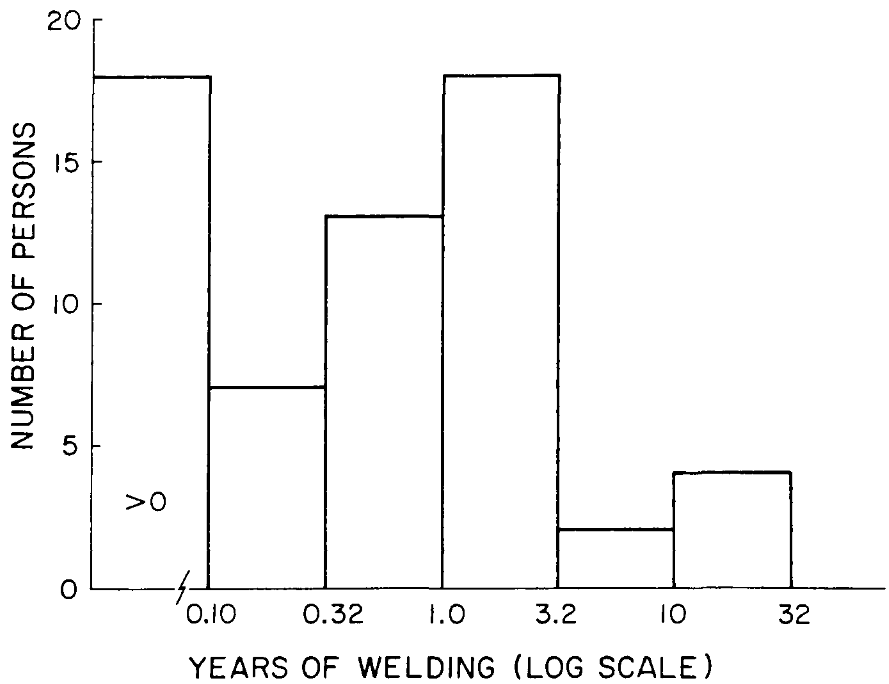

Fig. B6. Distribution of years welding for all those with any welding exposure whatever. A log scale is used, except for the first interval which extends down to but does not include zero. This interval contains many workers who are borderline between welders and non-welders.

Sample C. Technical Report Data Sheet, EPA Form 2220-1

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. 560/6-81-005

2.

3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE
MAGNETIC LUNG MEASUREMENTS IN RELATION TO OCCUPATIONAL EXPOSURE TO ASBESTOS MINERS AND MILLERS OF QUEBEC

5. REPORT DATE January, 1981

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S) David Cohen * Thomas S. Crowther ** ~~Graham W. Gibbs~~ [†] ~~Margaret R. Becklake,~~ [1]

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
American Public Health Association
1015 Fifteenth Street, N.W.
Washington, D.C. 20005

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO. 68-01-3859

12. SPONSORING AGENCY NAME AND ADDRESS
Office of Pesticides and Toxic Substances
U.S. Environmental Protection Agency
401 M Street, S.W.
Washington, DC 20460

13. TYPE OF REPORT AND PERIOD COVERED Final Report

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES Massachusetts Institute of Technology * ~~Celanese Canada, Inc.~~ [†]
U.S. Department of Labor --- OSHA ** ~~McGill University~~ [1]

16. ABSTRACT

Fe_3O_4 particles (magnetic) are often attached to asbestos fibers (non-magnetic) in the primary asbestos industries; therefore, a measurement of Fe_3O_4 could help determine the amount of asbestos in the lungs of workers in these industries. As a first assessment of this method of determining retained dust, magnetic measurements were made of the amount of Fe_3O_4 in the lungs of 115 miners and millers of chrysotile asbestos. The performance of these measurements at an industrial site was found to be feasible and practical. A relatively large amount of Fe_3O_4 was seen in the lungs of those with welding experience, which masked the Fe_3O_4 contributed by asbestos, therefore this group was considered separately. For the remainder (non-welders), the amount of Fe_3O_4 was plotted against a total dust exposure index which was available for each individual. The correlation between these quantities was not high, but was statistically significant at the 0.01 level. For the non-smokers within that group, the correlation was higher and the amount of Fe_3O_4 was relatively greater. These results suggest that the magnetic measurement of a chrysotile miner and miller reflects, at least to some extent, the amount of asbestos in his lung; the scatter could be due to individual differences in deposition and clearance, to which this measurement should be sensitive. These results are also consistent with the possibility that less dust is deposited or retained in smokers than in non-smokers.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Asbestos Occupational Exposure Magnetic Fe_3O_4	Amount of Fe_3O_4 in Lung Magnetic Dust Study Univariate Analysis	

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Unlimited	Unclassified	44
	20. SECURITY CLASS *(This page)*	22. PRICE

EPA Form 2220-1 (9-73)