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THE OPTIMUM SIZE OF RESEARCH GROUPS FOR MAXIMUM EFFECTIVENESS

Part I.—Statistical Formulation and Analysis of the Data for U.K., Canada and Pakistan

M. M. QURASHI*

P. C. S. I. R. Laboratories, Karachi 32

A statistical analysis is presented of the size distribution of laboratories and units of various major research organizations in three countries, *viz.* U.K., Canada, and Pakistan, using the concept of Density of Scientific Effort, defined in terms of the numbers, *N*, of the scientific officer class in various size-intervals. The individual distributions have somewhat varying shapes, and it is found that the mean data for agriculture research yield an excellent curve with a single maximum at $N=28\pm1$ scientific officers per institute and a half-value width of 45 ± 2. The data for industrial research, when averaged, give a distribution with the main peak at $N=69\pm1$ and a subsidiary maximum at 28 ± 2 scientific officers per institute or laboratory.

This bimodal distribution can be decomposed into two distributions, one of which is identical with that for agriculture research, while the other one is very different in nature, coming down to half-value at 52 and 95 scientific officers per laboratory or institute. All the individual distribution curves (including that for defence research establishments) are found to be made up of various proportions of these two basic distributions. It is concluded that the optimum number of scientific officers, N_{opt} for research institutes is given by $28 \leq N_{opt} \leq 69$.

1. Introduction

In an earlier set of papers[1,2] dealing with certain improvements in interview and selection procedures, and with optimum utilization of scientific talent, it was found that, by using a combination of academic grades up to the Intermediate science level and interviews directed towards aptitude-testing, it is possible to bring about a reasonably effective distribution of the available scientific talent into the three main streams of research and technological activity, thus:

(i) those well above a second division career make good research scientists,

(ii) those below a second division should be diverted away from research, and towards other scientific activity, such as technicians or junior assistants for supporting routine experimentation, and

(iii) those just making a second division on the average should be further graded by an interview or other aptitude test, so as to pick the 15% to 25% of this lot, who can become reasonably useful researchers and will probably also improve their academic grades; the rest would be diverted towards the category (ii).

As an offshoot of the above study, it was also considered worthwhile to examine some of the conditions under which optimum results can be expected from those ultimately taking up a research career. One of the important factors in this respect is the size of the group or unit in which a researcher operates, and a statistical survey of this aspect is attempted in the present communication. Data are examined from three countries, namely, U.K., Pakistan and Canada, and certain broad theoretical considerations are put forward for their interpretation and application.

2. Analysis of the Total 1960–61 Data for U.K.

An excellent and searching examination of the whole gamut of Government-controlled research and its organization was made in the beginning of this decade by a committee, headed first by the late Sir Claude Gibb and then by Sir Solly Zuckerman, which presented its report[3] on *The Management and Control of Research and Development* in July, 1961. In Chapter IX, dealing with organization, this report notes that "establishments are large in defence, where they are concerned mainly with applied research or with

*Now at P.C.S.I.R. Laboratories, Peshawar.

development work itself", while most of the units of the Agricultural and Medical Research Councils "are small ones..., which are concerned with highly specialized subjects, many having originally been built round the work of some outstanding research worker". The report, as will be seen from the data of Table 1 reproduced here, presumably implies 30 scientific officers as defining the line between small and large units.

Appendix IV of the above-mentioned report gives a synopsis of the sizes of the various research establishments, stations, units, etc., in terms of numbers of the scientific officer category (which corresponds to class I officers in Pakistan), and we present in Table 1 below a slightly modified form of some of this data for (a) the totality of the Government-controlled scientific organizations in column 2, and (b) the D.S.I.R. establishments only, in column 5. In the remaining two pairs of columns of Table 1, we have collected first the corresponding total numbers of scientific officers working in units of the size given in the first column, and then in the next column this same figure is corrected to a uniform *interval* of 10 officers, so as to make it representative of the Density of Scientific Effort in this interval. This measure of Density of Scientific Effort is plotted as ordinates against the middle of the corresponding unit-size interval in Fig. 1(a), and the smooth graph through these points is seen to show quite definite changes at values of 22 ± 5 and 110 ± 10 scientific officers/unit.

At each of these two sizes of unit, the Density of Scientific Effort drops by a factor of nearly 2, and one can justifiably correlate this with a change in the character of the unit. In fact, below a size of 20 officers, a unit is more in the nature of a field station, while the units having between 25 and 100 officers correspond to the range of sizes of full-fledged specialized laboratories, such as the National Chemical Laboratory or the Macaulay Institute for Soil Research.

3. Individual Distribution Curves for D.S.I.R., A.R.C., and Defence Research

With the above results in mind, we can now attempt a more detailed analysis of the graph of Fig. 1(a) by plotting individual distribution curves of the density of scientific effort for (i) the D.S.I.R. research stations, (ii) the Agricultural Research Council stations and (iii) the Defence Research establishments of the three armed services. The data for D.S.I.R. is already given in the right hand half of Table 1, and is plotted as crosses in Fig. 1(b). This graph is quite different from the plot of the total data, insofar as it is zero for small as well as very large values of N, the number of scientific officers per unit or station. It attains a maximum value of about 70 for $N = 42 \pm 5$ per station.

The corresponding data for the Agriculture Research Council and the Defence Research establishments is collected and converted into density of scientific effort in Table 2, where the number of units with less than 10 scientific officers has been multiplied by $\frac{2}{3}$, because many of these only carry out trials and data collection. While the data for the A.R.C. shows the same general pattern as the D.S.I.R., that for the Defence Research establishments appears to be somewhat different, particularly at small values of N. This is brought out clearly by the corresponding plots in Fig. 2. Fig. 2(a) shows that the distribution for the A.R.C. is similar to that of Fig. 1(b) with all values of N-reduced by a factor of about 0.7, the maximum being at 30 ± 4. instead of 42 in D.S.I.R. On the other hand, the plot of Fig. 2(b) for the Defence Research establishments is *not*

TABLE 1.—SYNOPSIS OF BREAKDOWN OF SCIENTIFIC INSTITUTES AND STATIONS IN THE U.K. ON THE BASIS OF NUMBERS OF SCIENTIFIC OFFICER CLASS IN ONE INSTITUTE.

No. of scientific officer class staff or equivalents	Total U.K. data			D.S.I.R. establishments only		
	Total no. of institutes, stations and units	Total no. of scientific officer class in the range	Scientific effort per interval of 10 officers	No. of institutes or stations	Total no. of scientific officer class in the range	Scientific effort per interval of 10 officers
1–2	20	30	150	—	—	0
3–9	80	500	500	0	0	0
10–19	32	480	480	4	65	65
20–29	14	350	350	2	50	50
30–59	18	810	270	5	232	77
60–99	10	800	267	2	155	39
100–139	5	600	150	1	107	27
140–179	2	320	80	1	164	41
> 180	1	300	20	0	0	0

Note.—The figures in the first and second rows are reconstructed from the original data.

only pushed out towards higher values of N by a factor of about 1.6, but also shows a small subsidiary peak close to the origin. It can presumably be looked upon as a composite of the two curves shown by the broken lines: each of these curves would have roughly the same general shape as the D.S.I.R. distribution of Fig.1(b), but widely different scaling factors for N. The data for medical research are not plotted separately, but these can be inferred from the initial peak in Fig. 1(a).

If, as a first approximation, we ignore the subsidiary peak of Fig.2(b), then we can define the shapes of the three distributions examined above by specifying a linear to parabolic rise with small N, followed by an approximately exponential drop after the maximum. Quantitatively, the shape of the distribution could approximately be defined in terms of two parameters, namely N_{opt}. the value of N at the maximum effort, and the half-value width, i.e. the difference between the two values of N where the density of effort falls to

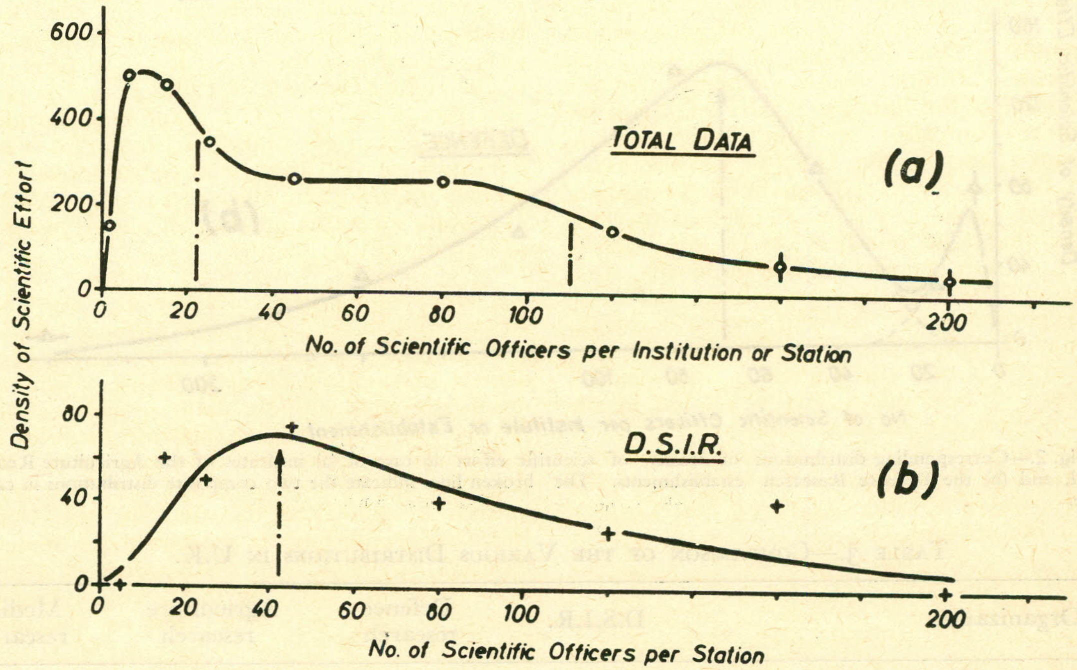

Fig. 1.—Plots of the distribution of Density of Scientific Effort for the U.K. in 1961, showing (a) the total data, which exhibits changes at 22 and 110 scientific officers per institute, and (b) the distribution for the various research stations of the D.S.I.R., which has its maximum near 42 scientific officers per station.

TABLE 2.—BREAKDOWN OF SIZES OF SCIENTIFIC INSTITUTES AND UNITS IN A.R.C. AND IN DEFENCE.

No. of scientific officer class or equivalent	Defence Research Establishments: No. of establishments and units	Total no. of scientific officer class in the range	Scientific effort per interval of 10 officers	Agricultural Research Council: No. of institutes and units	Total no. of scientific officer class in the range	Scientific effort per interval of 10 officers
< 10	$24\times\frac{2}{3}$	80	80	$20\times\frac{2}{3}$	67	67
10–19	2	30	30	8	120	120
20–29	1	25	25	11	269	269
30–59	6	270	90	6	245	82
60–99	7	560	140	1	71	18
100–139	$2\pm\frac{1}{2}$	240	60	1	103	26
140–179	$1\pm\frac{1}{2}$	160	40	0	0	0
> 180	1	~300	>20	0	0	0

Note.— The data for the units with less than 10 scientific officers have been multiplied by $\frac{2}{3}$, because many of these do only tests, trials and data collection.

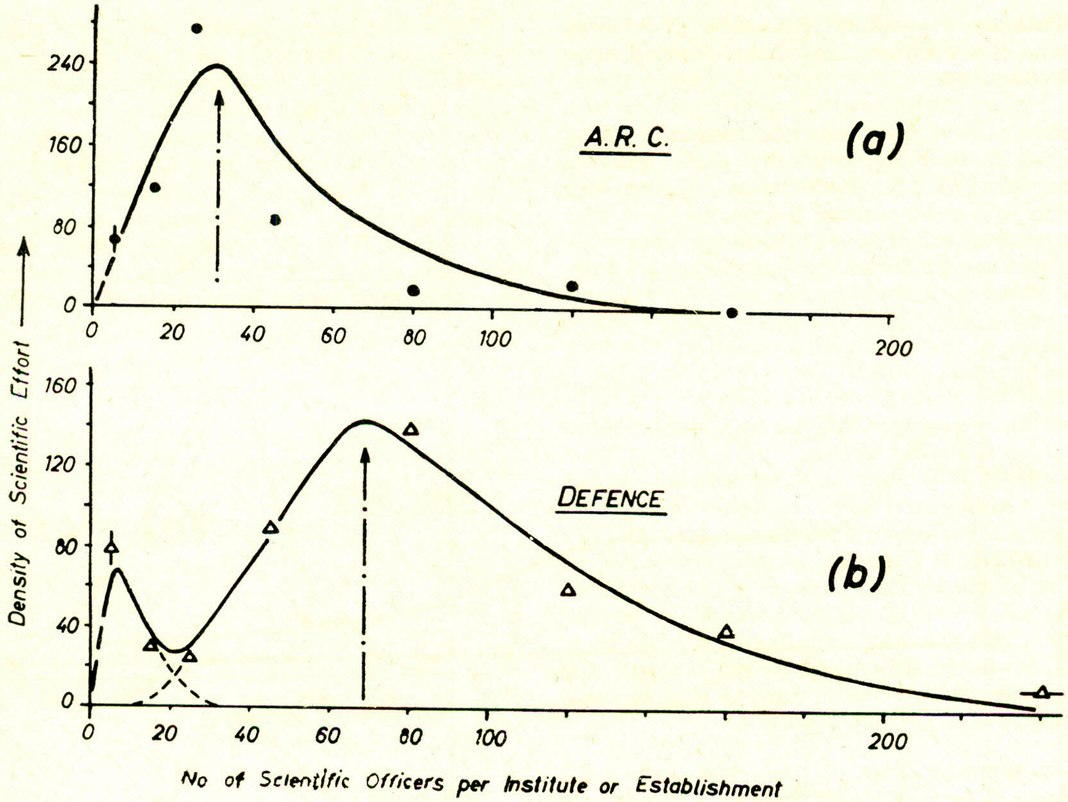

Fig. 2.—Corresponding distributions of density of scientific effort in case of (a) institutes of the Agriculture Research Council, and (b) the Defence Research establishments. The broken lines indicate the two composite distributions in case of defence.

TABLE 3.—COMPARISON OF THE VARIOUS DISTRIBUTIONS IN U.K.

Organization	D.S.I.R.	Defence research	Agriculture research	Medical research
Value of N at optimum effort	42	68	30	10
Half-value width	105–15=90	122–41=81	69–11=58	20–5=15
Ratio (N_{opt}/half-width)	0.5	0.8	0.5	0.6

half the maximum. The values of these two parameters are collected in Table 3 for the three research organizations studied above, along with the corresponding estimated data for the Medical Research Council, half of whose activity is distributed in units with less than 10 scientific officers, attached to various hospitals.

This table shows that with the exception of the Medical Research Council, the value of N_{opt}, the optimum number of scientific officers per research institute, varies from 30 for the Agriculture Research Council to 68 for the Defence Research establishments, while the corresponding half-value widths lie between 50 and 90. It is therefore worthwhile to examine the distribution of scientific effort among institutes of various sizes in similar organizations in other countries, so as to determine whether this is indeed the general pattern.

4. Some Distribution Curves of Scientific Effort in Canada and Pakistan

Accordingly, a similar analysis has been made of the data for two organizations in Canada and two in Pakistan, namely:

(a) The National Research Council of Canada and the Research Branch of the Canada Department of Agriculture, and

(b) Pakistan Council of Scientific and Industrial Research and Pakistan Atomic Energy Commission.

The data, which are obtained from the official reports of these organizations[4–7] for 1968 and 1967, are presented in Tables 4 and 5 in a form similar to that given earlier for the U.K. data in Tables 1 and 2. These additional data are plotted in Fig. 3 against the number of scientific officers, N, in each institute, the data for Pakistan having been combined into a single graph in Fig. 3 (c), because of the relatively low values of density of scientific effort in this case. A study of Fig. 3 shows that the peak density of scientific effort for the agriculture research activity in Canada occurs at about 30 scientific officers, while for the other two graphs it falls near 68 scientific officers per institute. Moreover, there is quite probably a small initial maximum at about 20 scientific officers in case of Pakistan, as was also observed in Fig. 2(b) for Defence Research establishments in U.K. A synoptic comparison of the several data for U.K., Canada and Pakistan is given in Table 6, from which the data on medical research have been omitted, because most of it is in small units attached to various hospitals.

It now appears that (i) the parameters for Agriculture Research in U.K. and Canada are practically identical, and (ii) the U.K. data on industrial and defence research, as well as those for Pakistan and Canada are rather similar to each other, having values of N_{opt} between 42 and 68, and half-value widths of the curves for density of scientific efforts varying from 44 to 90. We can now justifiably plot a mean curve for the U.K. and Canadian distributions of scientific effort in agriculture. This mean curve is plotted in Fig. 4(a), and we see that (i) the scatter of the points about the curve (± 12) is now very much smaller than for the individual curves, and (ii) the peak of height 190 occurs at $N=28\pm 1$ scientific officers, while the density of effort drops to half-value at 9 ± 1 and 54 ± 2 scientific officers per institute.

5. The Two Basic Distributions and Their Application

A similar averaging can be attempted with the corresponding curves for the other civilian research organizations whose parameters are listed in Table 6. The results are shown in Table 7 (with U.K. data recast at intervals of 10 all the way up to 60 scientific officers per establishment) and Fig.4(b), where a smooth graph has been drawn through the plotted points, the scatter of which is a little less (about ± 10) than in Fig. 4(a). This

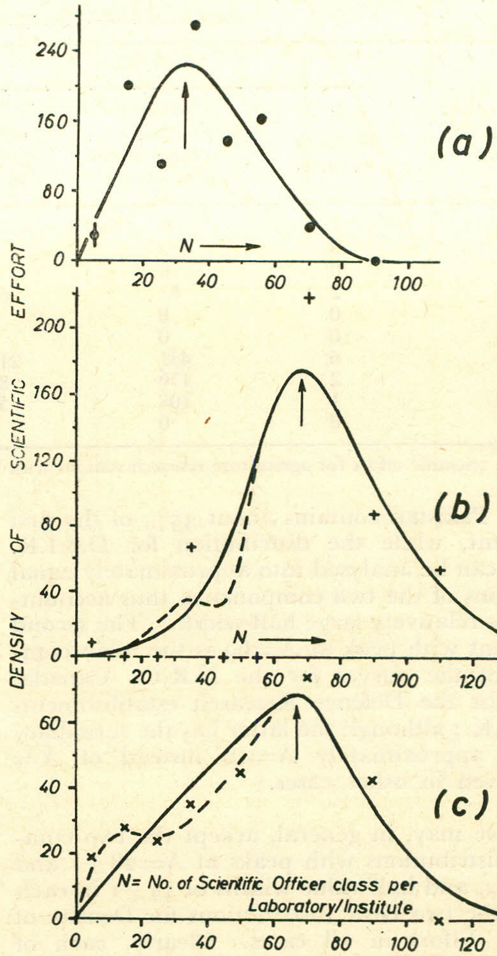

Fig. 3.—Distributions of Density of Scientific Effort among the various sizes of institutes and laboratories of (a) the research branch of the Canadian Department of Agriculture (1967), (b) the National Research Council of Canada (1968), and (c) the P.C.S.I.R. and P.A.E.C. (1967). The broken lines in Fig. 3(b) and (c) indicate the probable existence of a significant secondary maximum at $N\simeq 20$, in addition to the main peak at $N\simeq 70$ scientific officers per institute or laboratory.

smooth graph is bimodal, with the main peak at $N=69$, and a smaller subsidiary maximum at $N\simeq 30$, and it can be considered as a composite of two distributions, as shown by the broken lines in Fig. 4(b), viz. (i) one with a peak of height 38 at $N=28\pm 2$ and (ii) the other with a peak of height 104 at $N=69\pm 2$, and dropping to half-value at $N=52$ and 95. The first distribution is nearly identical in position and shape with that found in Fig.4(a) for agriculture research. It now appears that all the distributions of scientific effort so far found can be represented by suitable combinations of these two component distributions. Thus, the distribution of Fig.3(c) for the scientific

TABLE 4.—BREAKDOWN OF SIZES OF SCIENTIFIC INSTITUTES, DIVISIONS, AND STATIONS OF N.R.C. AND AGRICULTURE RESEARCH IN CANADA (1967–68).

No. of scientific officer class or equivalent	N. R. C.			Department of Agriculture Research		
	No. of divisions or units	Total no. of scientific officer class in the range	Scientific effort per interval of 10 officers	No. of institutes or stations	Total no. of scientific officer class in the range	Scientific effort per interval of 10 officers
< 10	1	8	8	6	43	$43\times\frac{2}{3}$
10–19	0	0	0	14	200	200
20–29	0	0	0	4	111	111
30–39	2	67	67	8	269	269
40–49	0	0	0	3	137	137
50–59	0	0	0	3	163	163
60–79	6	431	216	1	77	38
80–99	2	176	88	0	0	0
100–119	1	108	54	0	0	0
120–139	0	0	0	0	0	0

Note.—The scientific effort for agriculture research stations with less than 10 officers has been multiplied by $\frac{2}{3}$ as in case of U.K.

effort in Pakistan contains about 35% of the first component, while the distribution for D.S.I.R. in U.K. can be analysed into approximately equal proportions of the two components, thus accounting for its relatively large half-width. The second component with peak at $N=69$ is the main component of the curves for the N.R.C., Canada, as also for the Defence Research establishments in the U.K.; although the latter has the subsidiary peak at approximately $N=10$ instead of $N=28$ observed in other cases.

Thus we may, in general, accept the two component distributions with peaks at $N=28\pm1$ and $N=69\pm2$, and half-value widths of 44 ± 1 in each case, as the two basic distributions for Density of Scientific Effort in all cases. Clearly, each of these basic distributions is the nett result of a number of interrelated factors, such as the degree of mutual interactions between research workers in the particular type of research activity, the relative amount of wasteful work generated by the increasing size of any unit, as envisaged by Parkinson,[8] and the cost-effectiveness of the whole system. While a detailed mathematical treatment of this is in hand and will be reported separately, it is clear that in any scientific research organization, the optimum number of scientific officers, N, for the units should be somewhere between the peaks of the two basic distributions, i.e.

$$28\leq N_{\text{opt}}\leq 69 \qquad (1)$$

It can be presumed that units having the number of scientific officers, N, between these two limits function with near optimum efficiency, and it is seen that there are 30% to 45% of this type of unit in various organizations. Those with N less than 28 or with N greater than 69 would require further examination in respect of performance. Remembering that there are two to four scientific workers supporting each scientific officer, one may expect that the bigger units will

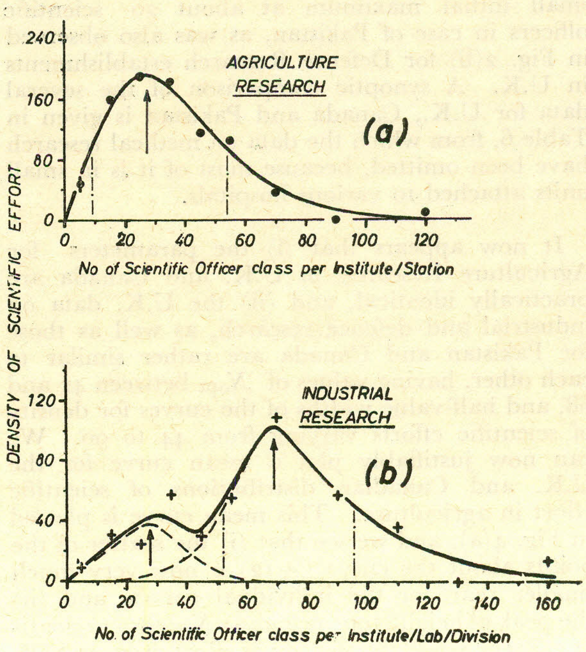

Fig. 4(a).—Mean distribution of Density of Scientific Effort for Agriculture Research in U.K. and Canada, showing the remarkably small scatter about the smooth mean curve, which has its peak at $N=28$ scientific officers per institute, and falls to half-value at $N=9$ and 54.

Fig. 4(b).—Corresponding mean distribution for industrial scientific research in U.K., Canada and Pakistan, showing the main peak at $N=69$, and a subsidiary maximum at N 28 ± 2. The broken line curves show the two component distributions, while the vertical chain-lines mark the points where the main distribution drops to half-value.

TABLE 5.—BREAKDOWN OF SIZES OF SCIENTIFIC INSTITUTES, LABORATORIES AND UNITS IN P.C.S.I.R. AND PAKISTAN ATOMIC ENERGY COMMISSION (1967).

No. of scientific officer class or equivalent	P.C.S.I.R.			Pakistan Atomic Energy Commission		
	No. of laboratories or units	Total no. of scientific officer class in the range	Scientific effort per interval of 10 officers	No. of laboratories or centres	Total no. of scientific officer class in the range	Scientific effort per interval of 10 officers
< 10	2	10	10	4	9	9
10–19	1	18	18	1	10	10
20–29	0	0	0	1	24	24
30–39	1	35	35	0	0	0
40–59	1	46	23	1	44	22
60–79	1	78	39	1	71	36
80–99	0	0	0	1	86	43
100–119	0	0	0	0	0	0

Note.—The data for the P.A.E.C. are subject to variations of as much as 15% due to training and other outside assignments.

TABLE 6.—COMPARISON OF PARAMETERS OF VARIOUS DISTRIBUTIONS FOR THREE COUNTRIES.

Organization	U.K. DSIR	U.K. defence	U.K. agriculture	Canada agriculture	Canada N.R.C.	Pakistan CSIR and AEC
N_{opt}	42	68	30	32	68	67
Half-value width	90	81	58	45	44	55±5
Ratio (N_{opt}/half-width)	0.5	0.8	0.5	0.7	1.5	1.2

TABLE 7.—AVERAGE DISTRIBUTION OF SCIENTIFIC EFFORT IN INDUSTRIAL RESEARCH FOR CANADA, U.K. AND PAKISTAN.

N	1–9	10–19	20–29	30–39	40–49	50–59	60–79	80–99	100–119	120–139	140–179
Canada	8	0	0	67	0	0	216	88	54	0	0
U.K.	0	65	50	68	0	164	36	41	54	0	41
Pakistan	19	28	24	35	90	0	74	43	0	0	0
Mean	9	31	25	57	30	55	109	57	36	0	13

suffer from the serious effects of "diminishing returns" and the wasteful expansion outlined by Parkinson.[8] The detailed mathematical treatment is expected to throw further light on the mechanics of this process and other interactions leading to the two basic distributions of scientific effort among units of various sizes.

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