Theory of Open-Contact Performance of Twin Contacts

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The first part is a presentation of an analytical study of the open-contact performance of twin contacts. It provides means for predicting their performance from single contact data. It is shown that the probability of failure of twin contacts is generally appreciably greater than the square of the probability of failure of single contacts. This is supplemented with the results of an experimental study which determines the effects of a few design parameters on the performance of single contacts. These are the parameters that determine the magnitude of improvement in performance obtained by replacing single contacts by twin contacts.

INTRODUCTION

The present switching apparatus normally operates in atmospheres that may be contaminated with dust particles and foreign matter. Some apparatus components, particularly the contacts, are relatively sensitive to such contaminations which may interrupt the proper functioning of a pair of contacts. Normally, a single switching operation in a central office requires the operation of as many as a thousand relays or 10,000 contacts. To secure the high level of performance desired, it is evident that superlative performance and high degree of reliability of the contacts are essential.

Many attempts have been and are being made to reduce the so-called "open" contact troubles due to foreign matter. Examples of environmental precautions are filtering the air supply to the central office, enclosing apparatus in cabinets, limiting personnel activities in the office, etc. An additional precaution incorporated in the apparatus design is the use of twin contacts. Such a scheme, when *properly* used, should result in substantial improvement in performance since an open can only take place when both members become open simultaneously. It may occur to one that the probability of a twin-contact open is the square of the probability of a single-contact open. Such a performance, however, has never been observed in practice where an improvement of only 10:1 is usually more typical. A study of the mechanisms involved has revealed that only a very small number of opens are obtained due to the simultaneous occurrence of opens on both members of a twin contact. The majority of opens, however, occur by having an open in one member of a twin contact which persists long enough to allow the occurrence of an open on the other member. By expressing this physical process in mathematical terms it was possible to develop a theory of performance of twin contacts in terms of the characteristics of single contacts.

NOTATION

d Diameter of dust particle
f Fractions of opens in single contacts cleared after N operations
f_∞ The asymptotic value of f corresponding to $N = \infty$
$\bar{n}$ Average number of operations required to clear an open on a single contact
r Distance of particle from center of circular open contact zone
r_0 Radius of "open zone"
s Fraction of the twin contacts that are half open at any time, $s = s_\infty + s_{\bar{n}}$
s_∞ Fraction of twin contacts that are permanently half open
$s_{\bar{n}}$ Fraction of twin contacts that are temporarily half open
w Mechanical wipe
x Average displacement of a dust particle per contact operation
F Contact force
N Number of contact operations
P_s Probability of occurrence of a single-contact open in opens/contact operation
P_t Probability of occurrence of a twin-contact open in opens/contact operation
X Total displacement distance to clear an open
α $= (2 - P_s)(1 - f_\infty)$
β $= \bar{n} f_\infty P_s (2 - P_s)$
θ Angle of displacement
φ Slope of contact surface irregularity

PRESENTATION OF THEORY

Outline and Assumptions

Consider a large group of twin contacts each constituting a pair of identical and entirely independent single contacts. After a period of operation a certain number of the twin contacts will become half-open.* These contacts will behave as if they were single-contacts until either: (1) the open half clears itself by operation, or (2) the other half becomes open leading to a twin-contact open. It is assumed that a failing twin-contact is cleared by an operator and then put back into service.

In developing the theory it was necessary to represent by analytic expressions the rate of occurrence of opens on single contacts and the rate of their clearing by operation. These are approximations of a fairly large amount of experimental data consistently obtained from a number of tests on a variety of actual telephone relay contacts.

(1) Rate of opens of single contacts "P_s": For a large number of single contacts at one set of operating conditions, the rate of opens is usually constant. This constant depends primarily on the quality and concentration of the offending foreign matter involved, the design of the contacts and their mechanism of actuation. Fig. 1 shows the results of three tests on single contacts of different design at different test conditions. They all substantiate the assumption that the rate of opens of

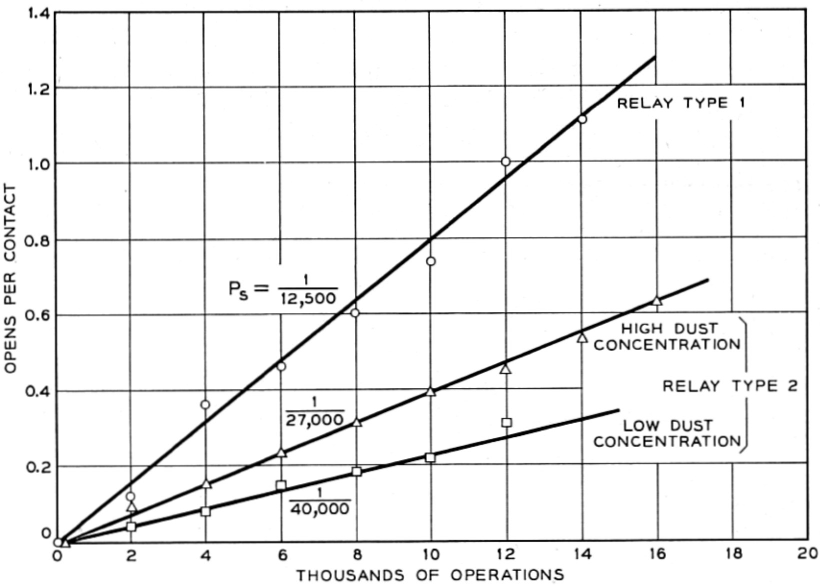

Fig. 1 — Rate of opens of single relay contacts.

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* A half-open is defined as one where only *one* member, of a pair in a twin-contact, is open. In practice, a half-open is not normally detected. Only a simultaneous open on both members of a twin contact will cause a circuit failure.

single contacts is a constant:

$$P_s = \text{constant} \tag{1}$$

where P_s is defined as the number of opens per "contact operation." In some cases, a certain transient period may precede the equilibrium characteristic "P_s = constant characteristic." This transient period is usually relatively short and is neglected in this analysis.

(2) Clearing of opens on single-contacts by operation: If an open single contact is allowed to operate mechanically, it is possible that it will clear itself after a number of operations. As discussed in a later section, the opens obtained are never identical in nature. They, instead, have a certain statistical distribution which usually accounts for a wide spread in their clearing rate. If, however, the operating conditions are under control, the clearing characteristic of a set of contacts is found to follow a well defined and reproducible statistical distribution. Fig. 2 shows an accumulative distribution curve for clearing opens produced by cotton lint fibres.* The ordinate represents the fraction of the open single contacts that clear after N operations as given by the abscissa. In general, these relations have the following typical characteristics. The first operation following the occurrence of the open is the most efficient† single operation in clearing opens. It is usually responsible for clearing 10 to 30 per cent of the total number of opens. The subsequent operations are progressively less efficient and in general a certain fraction

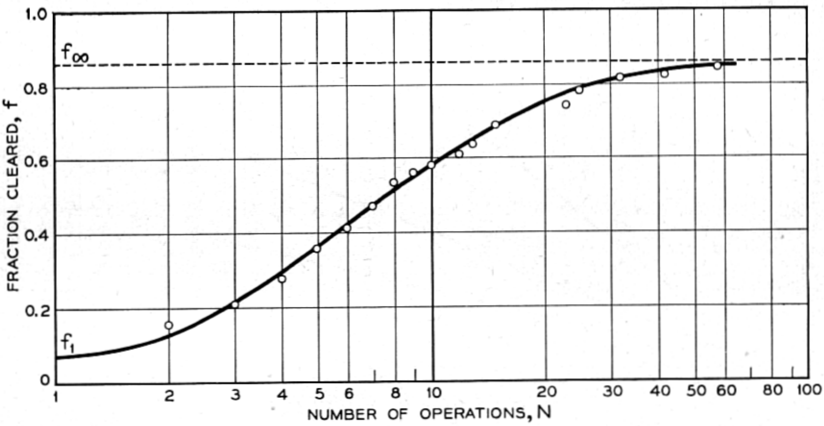

Fig. 2 — Distribution of clearing opens caused by lint.

* This is one of the major causes of open contacts in central offices. These fibres are usually in ribbon form of various configurations.

† This apparent efficiency is only due to the presence of opens that are more easy to clear than others. These will readily clear after one or a few operations.

$(1 - f_\infty)$ of the opens will persist for a relatively large number of operations. A study of a variety of these clearing characteristics generally indicates a rapid rise to the asymptotic value f_∞ in less than 100 operations, and to $f = 0.5$ in less than 10 operations. As will be shown the fractional persistency $(1 - f_\infty)$ is of major importance in determining twin-contact performance. In general, however, opens on twin-contacts are due to both the persistent half-opens and the temporary half-opens that might develop into twin-opens before clearing takes place.

DEVELOPMENT OF THE THEORY

Consider a large number of contacts operating at steady conditions. After N operations, let s_∞ be the fraction of the contacts that is permanently half-open and $s_{\bar{n}}$ be the fraction that is temporarily half-open. As discussed, the number of operations necessary to clear a half-open is not constant and, for the majority of the contacts, is of the order of a few operations. To simplify the treatment, it is assumed that each temporary half-open will clear in an average of $\bar{n}$ operations *from the time it first occurred.* The fraction $s_{\bar{n}}$ must, therefore, have been produced during the $\bar{n}$ operations directly preceding the time t. Since $\bar{n}$ is usually relatively small, the universe can be assumed to have had a negligible change during the operations $\bar{n}$. Hence,

$$\begin{aligned} s_{\bar{n}} &= (\text{rate of formation of temporary half-opens}) \times \bar{n} \\ &= \bar{n}[2(1 - s)P_s - (1 - s)P_s^2]f_\infty \end{aligned}$$

where s = total fraction of half-opens $= s_{\bar{n}} + s_\infty$. Substituting $\beta = \bar{n}f_\infty P_s(2 - P_s)$ one gets

$$s_{\bar{n}} = \frac{\beta}{1 + \beta}(1 - s_\infty) \tag{2}$$

Also, after N operations, the incremental change ds_∞ due to dN operation is:

$$ds_\infty = [2(1 - s)P_s - (1 - s)P_s^2](1 - f_\infty)\, dN - s_\infty P_s\, dN$$

where the second term is the reduction in s_∞ due to occurrence of twin-opens. Substituting $\alpha = (2 - P_s)(1 - f_\infty)$ and combining with equation 2 to eliminate $s_{\bar{n}}$ give:

$$ds_\infty = -\frac{1 + \alpha + \beta}{1 + \beta}\left[s_\infty - \frac{\alpha}{1 + \alpha + \beta}\right]P_s\, dN \tag{3}$$

$$s_\infty = \frac{1}{1 + \alpha + \beta} + Ke^{-(1+\alpha+\beta)/(1+\beta)P_s N} \tag{4}$$

where K is an integration constant. Let at $N = 0$, $s_\infty = s_0$, which is a description for the initial conditions of the contacts. The solution becomes:

$$s_\infty = \frac{\alpha}{1 + \alpha + \beta}\left[1 - \left(1 - \frac{1 + \alpha + \beta}{\alpha} s_0\right)e^{-(1+\alpha+\beta)/(1+\beta)P_s N}\right] \tag{5}$$

The rate, or probability, of twin-contact failure is determined from:

$$P_t = sP_s + (1 - s)P_s^2 \tag{6}$$

Substituting from 2 and 5 into 6 and reducing gives:

$$P_t = P_s^2 + P_s(1 - P_s)\frac{\beta}{1 + \beta}\left[1 + \frac{\alpha/\beta}{1 + \alpha + \beta}\left(1 - \left(1 - \frac{1 + \alpha + \beta}{\alpha} s_0\right)e^{-(1+\alpha+\beta)/(1+\beta)P_s N}\right)\right] \tag{7}$$

where, one may repeat for convenience:

$$\alpha = (2 - P_s)(1 - f_\infty) \text{ and } \beta = \bar{n}f_\infty P_s(2 - P_s)$$

For all practical cases, $P_s \ll 1$, $\alpha = 2(1 - f_\infty)$ and $\beta = 2\bar{n}f_\infty P_s < 1$. Substituting in 7 gives

$$P_t = P_s^2 + 2P_s\left[\bar{n}f_\infty P_s + \frac{1 - f_\infty}{3 - 2f_\infty}\left(1 - \left(1 - \frac{3 - 2f_\infty}{2(1 - f_\infty)} s_0\right)e^{-(3-2f_\infty)P_s N}\right)\right] \tag{7'}$$

This is a general expression, relating the expected performance of twin-contacts to that of single contacts. It is evident that the idealistic performance of $P_t = P_s^2$, i.e., the probability of a twin-contact failure is the square of that for single contacts, can only be achieved if: (a) $f_\infty = 1.0$, i.e., persistent half-opens never occur, (b) $\bar{n} = 0$, i.e., each temporary half-open occurring during one operation will clear during the subsequent operation, and (c) $s_0 = 0$, i.e., there is no initial contamination. These conditions are never obtained in practice and generally P_t is much greater than P_s^2.

Equation 7′ also indicates that at the beginning of operation, when the exponent is much less than 1.0, P_t is given by:

$$(P_t)_0 = P_s^2(1 + 2\bar{n}f_\infty) + P_s s_0 \tag{8}$$

Numerically if $\bar{n} = 50$, $f_\infty = 1.0$ and $s_0 = 0$, $P_t = 101P_s^2$ which is 101 times worse than the idealistic performance of $P_t = P_s^2$. The initial rate of failure of twin contacts is also quite sensitive to initial contact contamination. If, for example, $s_0 = 10^{-3}$, i.e., $1/1000$ of the twin contacts are permanently half-open to start with, and for the same numbers used above and $P_s = 1/10^6$, equation 8 gives $P_t = 1.1 \times 10^{-9}$. This corresponds to an 11 fold increase in twin-contact failures just due to an initial contamination s_0 of 0.1 per cent. This performance is also 1100 times worse than the idealistic performance of $P_t = P_s^2 = 10^{-12}$.

By operation, the performance of twin contacts will exponentially deteriorate according to equation 7. It will asymptotically approach a constant rate of failure given by:

$$(P_t)_\infty = P_s^2(1 + 2\bar{n}f_\infty) + 2P_s \frac{1 - f_\infty}{3 - 2f_\infty} \tag{9}$$

This is independent of the initial contamination s_0 and is practically reached in a number of operations:

$$(n_t)_\infty = 3/(P_s(3 - 2f_\infty)) \tag{10}$$

The worst performance of twin contacts is obtained when $f_\infty = 0$, i.e.,

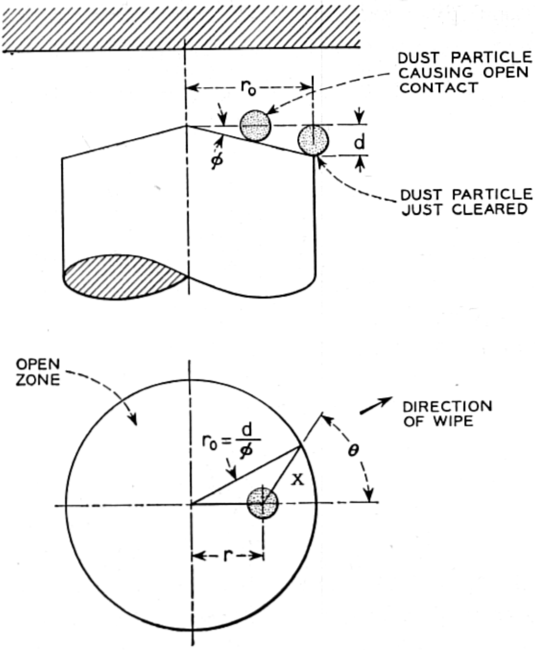

Fig. 3 — Particle in open zone.

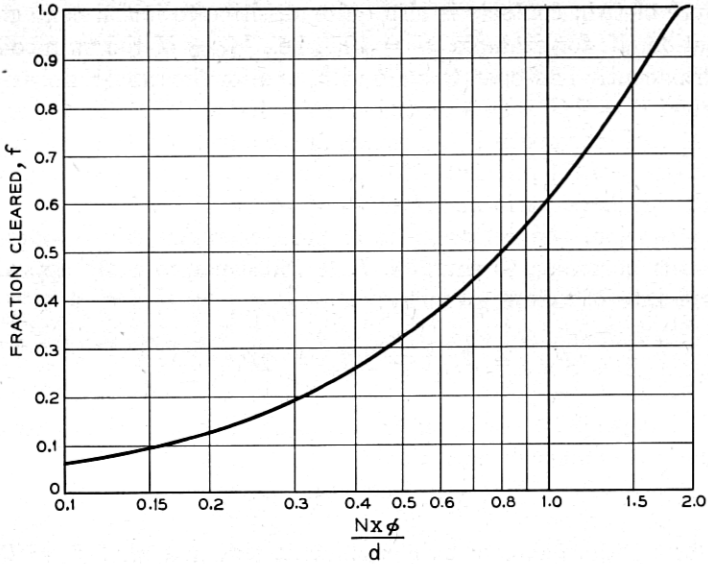

Fig. 4 — Accumulative probability distribution of fraction cleared "f" versus ($Nx\varphi/d$).

every half-open persists indefinitely, and is given by $(P_t)_\infty = \frac{2}{3}P_s$. In other words, *by replacing single contacts by twin contacts the frequency of failures is decreased by only one third.* In practice, however, f_∞ is rarely that low and under the wide variety of central office conditions it may range between 0.85 and 0.98. This corresponds to a range of performance of $P_t = 0.23\ P_s$ to $0.038\ P_s$ or the frequency of twin-contact failures is about $\frac{1}{4}$ to $\frac{1}{26}$ that of single contacts.

CLEARING AN OPEN BY MECHANICAL OPERATION

Introduction

Fig. 3 shows a diagrammatic sketch of the contact area with spherical particles preventing metallic contact. The surface irregularity has a slope φ and the particle diameter is d. It is evident that the particle will produce an open if it falls within a limiting radius $r_0 = d/\varphi$. The area within r_0 is called the "open zone." For a particle at a radius r within the open zone, mechanical wipe w will tend to displace the particle at an angle θ, $0 \leqq \theta \leqq 2\pi$. The open is cleared when the particle is displaced a distance X sufficient to drive it out of the open zone. For unidirectional wipe, if the average displacement per operation is x, the number of operations required to clear an open is $N = X/x$. Since, however, the initial location of the particle r has a triangular probability distribution, $0 \leqq r \leqq r_0$, and the direction of wipe θ has a rectangular distribution, $0 \leqq \theta \leqq 2\pi$, the number of operations for clearing must have a corresponding probability distribution. This has been determined graphically and is shown in Fig. 4. This is an accumulative probability distribution of the fraction cleared "f" versus $(Nx\varphi/d)$. It indicates that 50 per cent of the opens will clear at $(Nx\varphi/d) = 0.8$ and 100 per cent at 2.0. The corresponding number of operations N can be determined only if x is known* under the operating conditions. By increasing the contact wipe w one may expect x, the average displacement per operation, to increase. Also by increasing the force, the frictional driving force will increase and x should also increase. One may, therefore, tentatively assume that x is proportional to w^aF^b and the distribution function may be put in the form $f = f(Nw^aF^b)$, keeping all the other parameters fixed. This suggests that by varying the contact wipe w and the contact force F, the distribu-

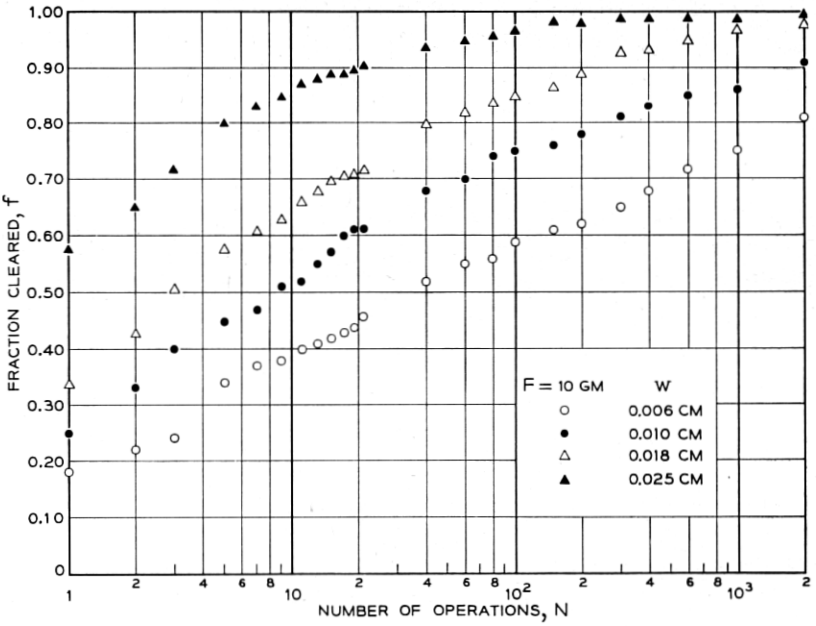

Fig. 5 — Effect of wipe.

* For a certain surface roughness φ and particle size d.

tion function f should be unique if plotted against Nw^aF^b where the a and b are constants to be determined experimentally.

Experiment

Cotton lint fibres and clean contact surfaces were used exclusively in this study. The fibres were essentially in the form of ribbons a few microns thick and of variable width and length. By using a dust separator,* lint fibres with a well controlled size distribution were collected on a glass plate. The setting used gave a rather uniform monolayer of fibres 80 per cent of which had a width between 10 and 20 microns.

The contacts tested were flat and made of palladium.† They were cleaned with methyl alcohol and distilled water, then dried. The collected lint fibres were transferred to the surface of one contact by a special adapter which allows the pressing of the contact on the glass

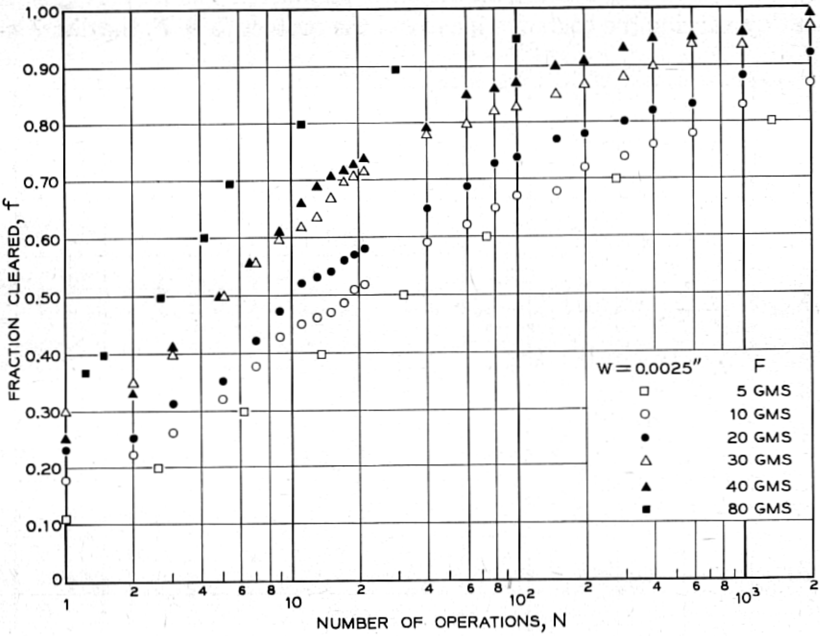

Fig. 6 — Effect of force.

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* Based on controlling sedimentation by adjusting air speed in a two-stage separator.

† Contact surface roughness was controlled by frequently polishing the contact surfaces by a fixed process.

plate with the fibres. The pressing force was the same as that used in the subsequent operation of the contacts. The contacts were then operated at four operations per second in a sealed compartment. After each closure a checking circuit using 48 volts, and a maximum current of 0.50 amp., checked the continuity in the contacts. When the open was cleared the unit automatically stopped and the corresponding number of operations was obtained from a counter. The maximum number of operations allowed for each run was 2,000. For one set of operating conditions, it was necessary to repeat the above for at least 150 times before a representative clearing distribution was obtained.

Results

Effect of wipe: Fig. 5 shows the results obtained for a range of wipes between 0.006 and 0.025 cm at a constant force of 10 grams. As expected, the clearing rate was higher for larger wipes.

Effect of force: Fig. 6 was obtained at a constant wipe of 0.006 cm and a set of forces between 5 and 80 grams. Large forces gave higher clearing rates. The effect of changing the force, however, is not as significant as that of changing the wipe.

As outlined in the preceding introduction, the above data was replotted as fraction clearing f versus Nw^aF^b. The results are shown in Fig. 7 with $a = 3$ and $b = 1.0$. As indicated, the points converged to a single average line with comparatively small spread.* This shows that, at least for the range covered, the change in clearing rate obtained by changing the wipe say by a factor of two can also be obtained by changing the force by a factor of 8.

To determine the persistency $(1 - f_\infty)$, one may choose an arbitrary number of operations for defining it. If 2,000 operations is chosen, one may determine from the above data the fraction, $(1 - f_{2,000})$, that will persist to beyond 2,000 operations. This was done and the results are plotted in Fig. 8 as $(1 - f_{2,000})$ versus $F^{1/3}w$. This suggests the following relation:

$$(1 - f_{2,000}) = e^{-F^{1/3}w/0.006} \tag{11}$$

where F is in grams and w in cms. This expression allows the determination of the effects of force and wipe on the performance of twin contacts by substituting in Equations 7′ through 10. Similarly the average number of operations $\bar{n}$, used in the above equations, may be obtained. This may

* This same convergence was obtained, but not presented here, by plotting f versus NF at constant w and f versus Nw^3 at constant F.

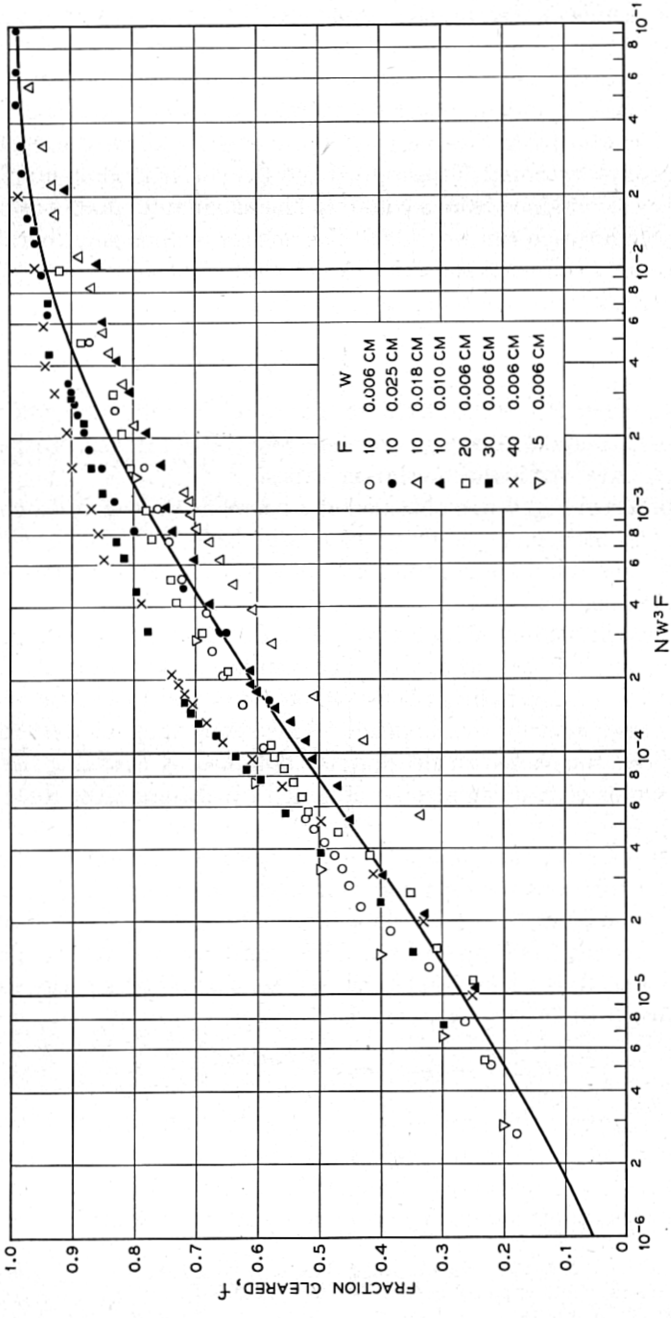

Fig. 7 — Average experimental curve; fraction cleared "f" versus Nw^3F.

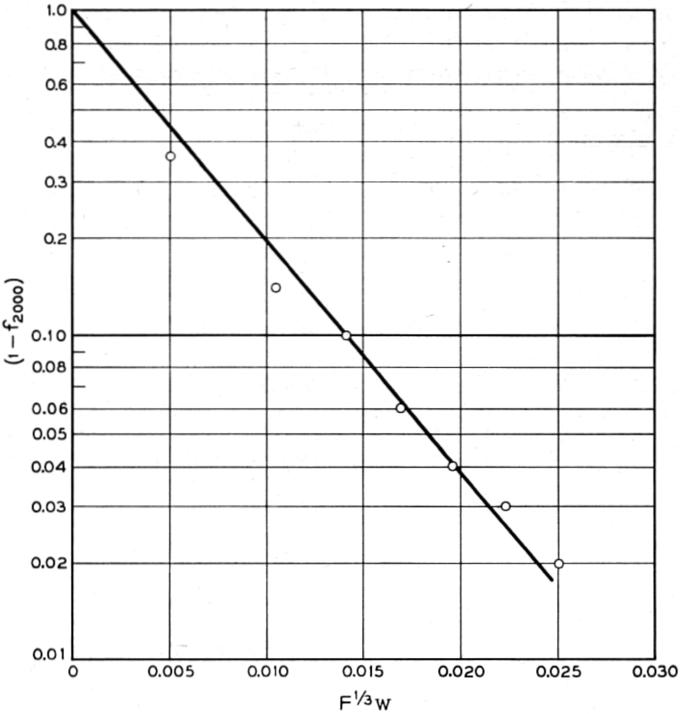

Fig. 8 — Persistency of opens at 2,000 operations.

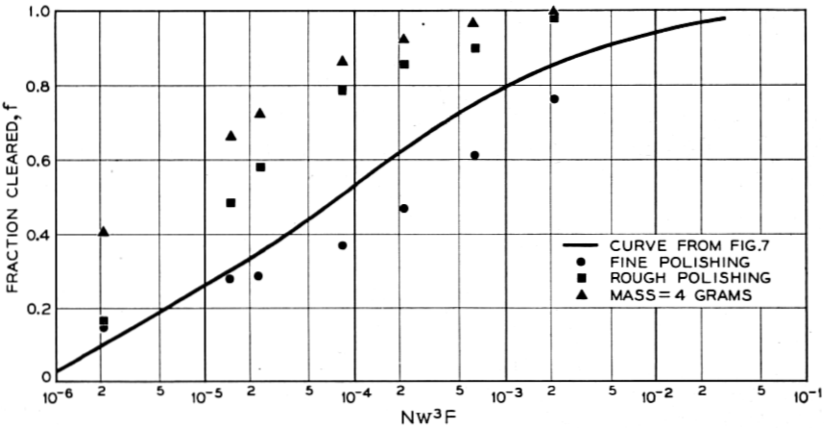

Fig. 9 — Effect of other parameters.

be arbitrarily defined as the number of operations at which 50 per cent of the opens will have cleared. At this or any other value of f one obtains from Fig. 7 $\bar{n}Fw^3 = $ constant or $\bar{n}$ is inversely proportional to Fw^3.

OTHER EFFECTS

Fig. 9 shows the results obtained by varying other parameters. The solid line, obtained from Fig. 7 is shown for comparison. Indicated are the effects of fine polishing and rough polishing of the contact surfaces and of increasing the mass of the moving contact from 0.5 to 4 grams.