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Human Factors and Behavioral Science:

Human Factors Comparison of Two Fiber-Optic Continuous-Groove Field-Repair Splicing Techniques

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Two Bell System fiber-optic splicing techniques that are under development were experimentally compared in a human factors study. In addition to splicing technique, the variables explored were the uniformity (evenness) of fiber spacing in the 12-fiber "ribbon," and the hand (preferred or nonpreferred) that was used to splice. Performance was measured by the time to insert fibers, the number of fibers broken, and the time taken to complete a series of insertions for each technique. The preference of the participants between the two techniques was also determined. All of the measures except participant preference showed the vacuum technique to be statistically superior to the hold-down bar technique, with participant preference suggesting the same conclusion, although it was not statistically significant.

I. INTRODUCTION

A human factors study compared two techniques under development for the repair splicing of damaged Bell System fiber-optic cable in the field. The goal of the study was to determine the preferred technique from a human factors viewpoint. This information combined with economic considerations would then allow the technique's designers

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to choose one of the techniques for further development and release to operating telephone companies.

II. DESCRIPTION

Bell System fiber-optic cable consists of one to twelve multiple-fiber "ribbon" arrays. Each ribbon consists of twelve optical fibers embedded in a plastic tape. Currently, each ribbon of the cable is shipped with a silicon connector on each end to facilitate the splicing (joining) of the ribbons of one cable section to the ribbons of the next section.[1] In joining one ribbon to another, the splicer first places silicon wafers on either side of one ribbon array connector, forming a sandwich, and secures this arrangement with a spring clip. The second ribbon connector is then slipped into this sandwich and a second spring clip is added. The final operation consists of the application and curing of a refraction index-matching gel.

These procedures are reasonably straightforward and have been successfully used by operating telephone companies. On the other hand, in certain situations the splicer must refabricate a ribbon's silicon connector in the field.[2] Refabrication is required when the fragile silicon ribbon connector is received damaged, is damaged in craft handling, when it is necessary to reposition ("swap") fibers within the ribbon, or when an additional splice point becomes necessary. In part, refabrication involves grinding and polishing of the individual fiber ends in the reconstructed silicon connector to minimize losses when the connector is spliced (joined) to another connector. Although field refabrication is successfully being done by operating telephone companies as the field-repair method, the two techniques described in this report are being developed to simplify field-repair splicing basically by eliminating the grinding and polishing operations.

Figure 1 schematically depicts the continuous-groove approach shared by the two splicing techniques. In both techniques, the silicon array connectors are first removed from the ribbons to be spliced. After fiber preparation, which includes removing the plastic tape, removing the individual fiber coatings, and developing square fiber ends, fibers of one ribbon are "combed" into the set of 12 continuous grooves. The fibers of the second ribbon are then similarly inserted into the continuous grooves. Once the fibers of each ribbon are inserted, they are brought into proximity and index-matching gel is applied and cured as in the standard joining procedure. Thus connector refabrication, with its necessary grinding and polishing steps, and the subsequent connector joining have been eliminated and replaced by a single operation.

The two continuous-groove techniques that were evaluated differ in the method for inserting fibers into the continuous grooves. The

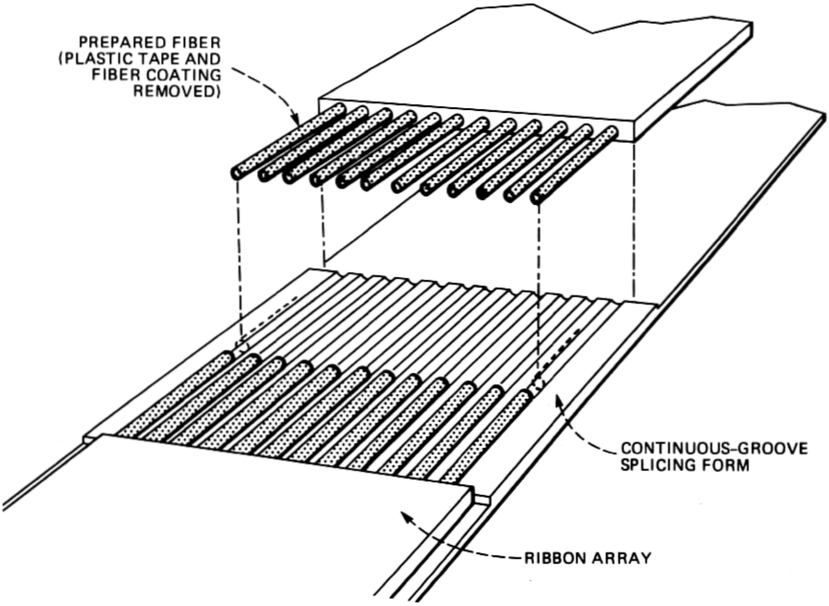

Fig. 1—Basics of a fiber-optic ribbon, continuous-groove splice.

vacuum technique uses a vacuum assist to help secure both the prepared fibers (tape and coating removed) and a portion of the ribbon beyond the prepared fibers. The splicer then uses a lateral motion to "coax" the 12 fibers into their respective grooves. In the hold-down bar technique, the splicer combs the prepared fibers into their respective grooves with the use of an alignment comb without any additional aid. The splicer first registers the twelve prepared fibers in the twelve slots of the alignment comb and then carefully pulls the ribbon back until the ends of the fibers go below a bar in the comb and fall to the continuous grooves below. The splicer then gently pushes the ribbon forward under the bar that holds the ribbon in the continuous grooves (hence the "hold-down bar" name), and pushes the ribbon along the continuous grooves to approximately the middle of the splicing form. The proprietary nature of these techniques, which are still under development, prohibit the use of photographs to illustrate the two techniques.

III. HUMAN FACTORS EXPERIMENTAL COMPARISON OF SPLICING TECHNIQUES

A human factors study was designed to compare the two field-repair splicing techniques on the basis of craft performance. An analysis of the sequence of operations in the techniques suggested that the only difference between fully developed techniques would be the method of inserting fibers into the grooves. Both techniques would likely share the same or similar methods of fiber preparation, index-matching gel application, etc. Therefore, it was decided to limit the scope of this study to assessing performance differences between techniques for successfully inserting fibers into the continuous grooves.

3.1 Method

3.1.1 Design

The experiment was a within-participants design. Each participant was trained and tested under every combination of experimental variables. The three experimental variables were: splicing technique (vacuum or hold-down bar), fiber spacing uniformity (uniform or nonuniform), and splicing hand (preferred or nonpreferred).

Fiber spacing uniformity refers to the uniformity of spacing of the twelve fibers in the ribbon. Previous experience with handling of fibers showed that nonuniformly spaced fibers are more difficult to guide into grooved structures than uniformly spaced fibers. Nonuniformly spaced fibers can result from manufacturing and from the removal of the coatings on each fiber. Since nonuniform ribbons occur infrequently, they were created for the study by making a hole with a small awl in the plastic tape at the point where the prepared fibers emerge from the tape.

The third variable, splicing hand, was chosen to reflect the fact that *all* splicing techniques require the splicer to use both left and right hands on the ribbons coming from the left and right sides, respectively, and thus the potential interaction between splicing hand and field-repair technique is of interest. Although it is possible to rotate the splicing form so that the splicer uses the preferred hand for both ribbons, concern over building in transmission loss caused by bending the fibers precluded further consideration of this approach.

Four dependent measures selected to contrast the two field-repair techniques were:

1. Average insertion time
2. Number of broken fibers
3. Elapsed (clock) time
4. Participant preference.

Average insertion time, measured with the participants' knowledge, was the time between beginning an insertion and its successful completion. If a fiber was broken the clock was stopped, a new ribbon was provided, and the clock was restarted. Similarly, the clock was stopped and restarted if a question was asked or the experimenter wanted to clarify a procedure.

Elapsed (clock) time was simply the total time required to complete all 14 insertions required in each technique. It included training and questions in addition to the actual insertion time reflected in the average insertion time.

Participant preference was gauged at the end of the experiment by asking the question: "If you were a Bell System splicer, which of the two splicing techniques you used would you prefer to use on a regular basis?"

3.1.2 Experimental apparatus

The work platform measured 14 × 24 inches and was chosen to closely approximate the current splicing work station. This rather small area is dictated by the limitations of many splicing situations. A stand-mounted 3× magnifier to allow close viewing of the fibers (approximate 0.005″ diameter with coating removed) and splicing form, and two halogen lamps to evenly illuminate the work station were chosen as a result of previous work. A beam splitter plate, television camera, and monitor comprised the observation system that allowed unobtrusive monitoring of participant performance and the demonstration of insertion technique by the experimenter, as discussed below.

3.1.3 Procedure

Participants were individually tested in a session lasting approximately two hours. They were first familiarized with Bell System fiber-optic cable and current procedures for splicing ribbons together. Half of the participants were then trained and tested on the hold-down bar technique first, with the other half receiving the vacuum technique first.

Training consisted of the experimenter demonstrating the correct insertion procedure. Participants first watched "over the experimenter's shoulder" and then observed the detailed aspects on the closed-circuit television monitoring system. After this initial training, all participants performed the sequence of splicing insertions outlined in Table I.

The first insertion was designed as practice with the participant using a uniform ribbon and his or her preferred hand. In addition, the ribbon was free, i.e., it was not anchored at one end. All subsequent

Table I—Sequence of experimental ribbon insertions for both splicing techniques

Step	Fiber Spacing	Task
1	Uniform	Practice with free ribbon using preferred hand
2	Uniform	One practice insertion using preferred hand
3	Uniform	Six insertions alternating hands
4	Nonuniform	One practice insertion using preferred hand
5	Nonuniform	Six insertions alternating hands

insertions were timed with the 20-inch ribbon anchored approximately 16 inches from the splicing form to simulate a ribbon emerging from a cable.

As shown in Table I, nonuniform ribbons were not introduced until later in the splicing sequence, and thus any comparison of the effect of fiber spacing uniformity on splicing performance within a particular splicing technique is confounded by the additional training for nonuniform ribbons relative to uniform ribbons. This point will be discussed further in Section 3.2.

After completing the insertion sequence using one splicing technique, participants were given a five-minute break and then trained and tested in an identical manner using the other technique. After completing both techniques, participants were asked a short series of questions to obtain more detailed information on their performance. Questions were asked concerning any hobbies requiring fine motor control such as knitting, use of glasses (including bifocals) during the experiment or at other times, general comments, and their preference between the two field-repair techniques.

3.1.4 Participants

It was considered useful to select two distinct subpopulations as participants, each with some degree of demonstrated motor skill, in order to be able to generalize the results of the experiment to operating telephone company craftspeople. Nine people from the Bell Labs wiring shop and nine from the Bell Labs clerical pool participated.

3.2 Results

Performance of the two subpopulations, wiring shop and clerical, was virtually identical. The subpopulation variable was not significant ($F < 1$) and did not interact with any of the other independent variables. This similarity of results for the two subpopulations presumably reflects the fact that both groups did indeed possess a similar degree of general motor skill with which to approach the learning of this new motor skill.

3.2.1 Average insertion time

Figure 2 shows average insertion time for the nonpractice insertions (Steps 3 and 5, Table I) as a function of splicing technique and fiber spacing uniformity for all 18 participants. The superiority of the vacuum technique over the hold-down bar technique was significant [$F(1,16) = 19.6, p < 0.001, MS_e = 0.52$]. This statistical superiority of the vacuum technique was obtained despite the fact that four participants had to be stopped on one or more insertion attempts using the hold-down bar technique and the time to that point used as an

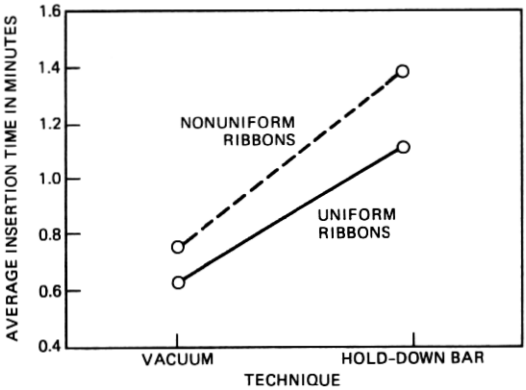

Fig. 2—Average insertion time on uniform and nonuniform ribbons for each splicing technique.

(under) estimate of that insertion attempt. Participants were stopped whenever an attempt exceeded approximately four minutes in order to allow completion of the experiment in a two-hour period.

The smaller average insertion time for uniform ribbons relative to nonuniform ribbons shown in Fig. 2 was statistically significant [$F(1,16) = 5.6, p < 0.05, MS_e = 0.23$]. As previously noted (and shown in Table I), nonuniform ribbons were presented after uniform ribbons, introducing a confounding between fiber spacing uniformity and training. However, since it is reasonable to assume that performance with the nonuniform ribbons benefitted from this additional training relative to the uniform ribbons, the smaller average insertion time for the uniform ribbons may be interpreted as a valid effect. Neither the interaction between splicing technique and fiber spacing uniformity, nor interactions between any of the other independent variables were statistically significant.

Participants performed marginally better with their preferred hand, although this difference was not significant ($p > 0.05$). The lack of an interaction between splicing hand and technique was surprising since a distinct preferred-hand advantage was expected for the hold-down bar technique given the motor skill required for this technique.

3.2.2 Additional measures

Table II contrasts the two field-repair splicing techniques using the other three dependent measures. The number of broken fibers was significantly less in the vacuum technique [$F(1,16) = 14.6, p < 0.005, MS_e = 3.25$]. No other main effects or two-way interactions were found using number of broken fibers as the performance measure. Elapsed (clock) time was also significantly less in the vacuum technique

Table II—Additional ribbon insertion measures

Measure	Technique: Vacuum	Technique: Hold-Down Bar
* Number of broken fibers (total)	4	24
* Elapsed (clock) time	33.6 min	56.9 min
Participant preference (total)	12	5

* Statistically significant at $p < 0.005$.

(Wilcoxon test, $p < 0.002$). Participant preference (with one abstention) favored the vacuum technique, although it was not significant as assessed by a Sign test.

IV. DISCUSSION

4.1 Vacuum technique superiority

The various measures strongly suggest the superiority of the vacuum technique over the hold-down bar technique. This superiority is basically a time advantage realized both directly in using the technique, and indirectly by reducing the number of repeated fiber preparations required when fibers are broken. However, it should be noted that 14 of the 18 participants were successful in completing all 12 of the nonpractice insertions required of them in the hold-down bar technique. Further, even the four participants who had to have one or more of their insertion attempts terminated because of time limitations completed at least 10 of the 12 attempts. This relative facility is important as it was not clear, a priori, whether inexperienced people could be easily trained to use the hold-down technique, especially with the brief (approximately 10-minute) training.

In interpreting the results of this study, it should be remembered that the study focused on only one of the operations required in field repair, i.e., ribbon insertion. Although ribbon insertion is undoubtedly the most difficult operation for the splicer, the time required by the other operations common to any field-repair technique may somewhat overshadow the vacuum technique time advantage. Thus, other factors such as economics and manufacturability are important in selecting the technique to be developed for release to the operating telephone companies.

4.2 Unanswered questions

Two relevant human factors concerns remain unanswered by this study. One unknown is the amount of additional training that would be required to improve the performance of those people experiencing difficulty with the hold-down bar technique. A second question is the stability of the learned field-repair skills over time, i.e., the memory for the skills. The ability to perform either technique will probably decrease as a function of the time since a person's last splicing experience. This forgetting is particularly relevant to the scenario in which a period of weeks or months elapses between splicing experiences. It is not clear, for example, that the vacuum technique would remain superior to the hold-down bar technique over time. Further studies will help to answer these questions.

REFERENCES

1. C. M. Miller, "Fiber optic array splicing with etched silicon chips," B.S.T.J., *57*, No. 1 (January 1978), pp. 175–90.
2. H. J. Friedrichsen and P. F. Gagen, "Optical cable field repair using array fabrication," 7th European Conf. on Optical Fiber Commun., September, 1981, Copenhagen, Denmark.

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