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A Method To Evaluate Human Factors/Ergonomics Design Variables of Distress Signals

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The selection and use of distress signals is crucial for a boater in any emergency. This situation is intensified by the fact that boaters are usually not familiar with such devices. Therefore, incorporation of human factors/ergonomics variables into the design of distress signals can be an important element in boater survival. This report presents a systematic method to evaluate and confirm the effectiveness of human factors/ergonomics variables in the design of distress signals. The effects of several identified variables were tested individually in the lab and synergistically in a (simulated) on-water emergency. It was found that emergency signals that were designed according to human factors/ergonomics recommendations generally required less time to operate than devices that did not follow such guidelines.

INTRODUCTION

Boater distress situations have been occurring in steadily increasing numbers. In 1977, the U.S. Coast Guard assisted about 75 000 recreational boaters (U.S. Coast Guard, 1979). The number of search and rescue cases is expected to increase by about 6% every year. In approximately 25% of all emergencies, the boaters are in moderate to serious personal danger. In 1977, more than 1000 boaters drowned (National Safety Council, 1978). One of the few aids to a boater in a distress situation is a distress signal (DS). Thus, it is important that the design of distress signals rely on human factors/ergonomics (HF/E) principles. Unfortunately, many distress signals are not designed for ease and speed of use (McHale, 1977; Miles, 1977).

DS Objectives and Parameters

A DS is used to notify others that an emergency situation exists and that help is needed, and to indicate the location of the party in distress. Often there is little time for a potential rescuer passing by in a boat or plane to see the signal. Thus, criteria for judging the design of a DS are (a) whether or not an operator can select from a number of DS one appropriate to the situation (packages of DS contain several kinds of devices, e.g., flares for night use, smokes for day use); (b) whether or not the device can be successfully activated (many DS are difficult to activate because of inadequate design or difficult instructions); (c) the time needed for successful selection and activation.

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Two types of boaters use signaling devices: the professional boater who should have had training in the use of signaling devices (but usually has not) and the recreational boater who has probably never been trained in DS utilization and who scrutinizes, selects, and operates a device for the first time in an emergency situation (Pieper and Cornell, 1975). Obviously, devices should be designed for the worst condition, i.e., for an operator with no training or experience.

DS Use

Use of a DS occurs in the three distinct steps shown in Figure 1. The first step is identification of the DS at hand and the ensuing selection of the device most appropriate for the situation. The operator needs to identify the function of the device (e.g., flare or smoke) and the mode of use of the device (e.g., hand held, thrown overboard, shot into the air). Closely associated with both is the manipulation necessary (e.g., ignite or unwrap). Design features of the DS should relay this information to the operator. In the second step, the device should be unwrapped and ready for activation in a minimum amount of time. Again, information is needed that indicates what actions must be taken (open box, remove wrapper, etc.). The third and final step in the device utilization process is the actual operation. The device should be activated quickly and at the desired time (e.g., when a plane flies by).

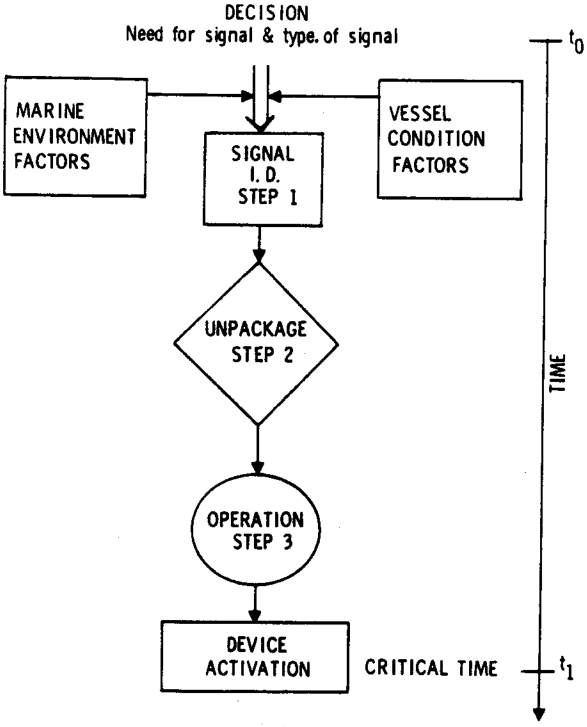

Figure 1. *Flow diagram of DS use.*

DS Improvement

Requirements for a distress signal have just been stated in terms of the steps of utilization. The design variables chosen should be a function of these objectives. This paper focuses on the development of a method to assess and validate objectively the usefulness of related design variables for devices available on the market. It is based on the results of a study sponsored by the U.S. Coast Guard (Kroemer and Marras, 1978).

METHOD

The study was performed in the following sequence: (a) survey of existing DS, pilot study, identification of independent variables, and compilation of HF/E design recommendations; (b) laboratory tests of the individual effects of selected design variables; and (c) field tests of the synergistic effects of design variables.

A large number of DS are currently on the market (see Figure 2). With the help of the U.S. Coast Guard, an attempt was made to include every type of marine distress signal available to the recreational boater. While it cannot be claimed that this goal was indeed achieved, no devices not previously known to the investigators were discovered during the period of investigation (1977-1978).

The DS were then categorized according to the steps involved in identification, un-

Figure 2. *Samples of common distress signals.*

packaging, and operation and as to the independent variables associated with these steps. To aid in this review, a pilot study was performed in which both experienced boaters and naive subjects were asked to select and operate diverse DS. Their performance was recorded on videotape. The taped subject performance was analyzed as a function of design variables. This identified independent variables associated with each step of the utilization process. They are listed in Table 1. For each one of these independent variables, HF/E recommendations were derived from the literature (McCormick, 1976; Department of Defense, 1970; MSFC-STD-267A, 1966; National Safety Council, 1978; Parker and West, 1973; Roebuck, Kroemer, and Thomson, 1975; U.S. Air Force, 1972; U.S. Army, 1975; VanCott and Kinkade, 1972). The actual implementation of these recommendations was judged, using the information from the videotapes. This established a hierarchy of design variables (and actual devices).

In the next phases of the study, variable effects on performance time were measured. The first phase (laboratory test) investigated the individual design recommendations in a controlled environment, while in the second phase (field test), the synergistic effects of several design variable recommendations

TABLE 1

Independent Variables in the Use of DS

Identification of		*Unpacking*	*Operation*
Function	*Mode of Use*		
Coding	*Coding*	*Manipulation*	*Manipulation*
Form	Form	Grip	Grip
Color	Size	Strength	Strength
Label	Color	Size	Size
Size	Label	Form	Form
		Motions	Motions
		Instructions	*Instructions*
		Legibility	Legibility
		Content	Content
		Location	Location

were investigated under simulated emergency conditions.

LABORATORY TESTS

Subjects

Fifteen male and 15 female college undergraduate students participated as subjects in this experiment. None of the subjects reported familiarity with any DS used in the experiments. All were volunteers and received $15 for their efforts. The mean age of the subject population was 22.33 yr, with a standard deviation of 2.02 yr.

Experimental Design

Two independent variables (stimuli) were chosen for each operation step, i.e., identification, unpackaging, and operation. As described below, each variable was divided into three treatment conditions, one which fully complied with the proposed HF/E recommendations (Condition 1), one which partially complied (Condition 2), and one which did not comply at all (Condition 3). All other variables were held constant.

The dependent variable was defined as the performance time required to achieve the particular objective of each test. Different subjects were then assigned randomly to a treatment group; each group was composed of five males and five females.

Apparatus

The apparatus for Test 1 (Identification—Shape Coding) consisted of three types of hand-held flares. For the independent variable, the primary stimulus was the presence (or absence) of a hand grip on the flare. Condition 1 was a common hand-held flare with a shaped handle. Condition 2 was a regular highway fusee with a cylindrical hand grip. Condition 3 was a regular highway fusee without a distinct hand grip. Secondary stimuli consisted of five other devices (parachute flare, self-contained aerial flare, self-contained smoke canister, and a combination smoke/flare), all dissimilar in shape from each other and from the primary stimuli. All stimuli (primary and secondary) were painted red and contained no labeling. In this way, all other variables except form coding were held constant.

The apparatus for Test 2 (Identification—Labeling) consisted of three orange plastic boxes (about 20 × 10× 5 cm). For Condition 1, a silhouette of a signaling pistol was put on the lid. The box for Condition 2 was lettered "signalling pistol" (lettering done according to Military Standard M-18012). Condition 3 was a plain box without any labeling.

The apparatus for Test 3 (Unpackaging—Wrappers) consisted of three identical common hand-held flares with wooden handles, each sealed in identical transparent plastic. The plastic bag for Condition 1 had a self-starting pull tab. The plastic for Condition 2 had a starter cut. The plastic for Condition 3 was not prepared to have any unpackaging aid.

The apparatus for Test 4 (Unpackaging—Latches) consisted of three boxes of approximately the same volume (3000 cm^3). The Condition 1 box could be opened via a lift-tab; the Condition 2 box could be opened via a self-starting pull tab; and the Condition 3 box could be opened via cross tabs (requiring one of the tabs to be pushed and the adjacent one to be pulled simultaneously).

The apparatus for Test 5 (Operation—Legibility) consisted of identical instructions, the lettering of which conformed to the Military Standard M-18012. However, the color contrast in Condition 1 was white characters on black background; black on white in Condition 2; and black on red in Condition 3.

The apparatus for Test 6 (Operation—Color Coding) consisted of three wooden cylinders of 3 × 25 cm, i.e., approximately the size of a hand-held flare. In Condition 1, half the cylinder was painted red and the other half white. In Condition 2, the cylinder was brown and red. In Condition 3 the colors were black and blue.

The actual tests were performed in a laboratory chamber (approximately 6 × 4 × 3 m) with no windows; thus lighting and noise levels could be controlled.

Procedure

Each subject was assigned to a trial order which contained two Condition 1 trials, two Condition 2 trials, and two Condition 3 trials. The conditions assigned to each test were counter-balanced to control for carry-over effects.

A stressful experimental environment (low-illumination/high-noise conditions) was created in the test laboratory. The lighting level was at 0.03 cd/m^2, and a constant 80-dB white noise was maintained in the test room. The subject was exposed to a preadaptation light level of 0.82 cd/m^2 for approximately 1 min prior to entering the room.

Subjects were informed that they should achieve the experimental objectives as fast as possible. The objective of Test 1 was to pick up a hand-held flare from the secondary stimuli (five other devices). In Test 2, the subject was to identify the box which contained a signaling pistol from the secondary stimuli (two similar boxes with no coding). The objective of Test 3 was to unwrap the device. In Test 4, the objective was to open a box. Test 5 required the subject to follow written instructions. The objective of Test 6 was to grasp a cylinder by the "safe" end. The times actually needed to perform these tasks were measured.

Between tests the subjects performed unrelated secondary tasks (elbow flexion muscle strength tests) which lasted about 10 min. This interruption of the primary test procedure was expected to dissipate any ordering effects and allow the subjects' visual systems to readapt to normal lighting conditions.

Results

The performance times are shown in Table 2. They were analyzed by one-way analysis of variance (ANOVA). For each test, the variances of performance times for each condition (1, 2, and 3) were considered. Table 3 presents ANOVA results of the testing. Test 4 (Unpackaging—Latches, $F\ (2,27) = 15.17, p \leqslant 0.05$, and Test 5 (Operation—Legibility), $F\ (2,27) = 6.29, p \leqslant 0.05$, were found to show significant trend effects, i.e., the better the design complied with HF/E recommendations, the more performance time was reduced.

Tests 1, 2, 3, and 6 were not significant in the ANOVA evaluation. In order to determine if the differences in the mean performance times were due to chance or were confounded by Condition 2 not being clearly "better" or "worse" than Conditions 3 and 1, respectively, Conditions 1 and 3 were compared via t-tests. The t-values for Tests 1, 2, 3, and 6 were all significant ($t_1 = 6.59, p \leqslant 0.01$; $t_2 = 8.87, p \leqslant 0.01$; $t_3 = 20.62, p \leqslant 0.01$; $t_6 = 12.12, p \leqslant 0.01$; d.f. = 18 in all tests). This indicates again that, in fact, Condition 1 brought about

TABLE 2

Results of Laboratory Tests: Performance Time in Seconds

	Device Condition					
	1		*2*		*3*	
Test No.	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
1	4.01*	7.44	5.58	2.28	5.50	3.13
2	3.86	2.0	4.82	2.30	4.82	2.79
3	18.90	13.94	27.33	14.72	37.91	25.45
4	5.94	1.15	23.23	9.80	12.89	7.22
5	21.67	7.87	33.63	17.78	55.55	32.07
6	3.82	3.99	4.56	1.82	4.96	1.99

*** Based on eight trials. All other data based on 10 trials.**

shorter performance times than Condition 3 in each test.

Discussion of the Laboratory Test Results

The ANOVA analysis for Tests 4 and 5 indicates that the designs selected (representing gradual differences in compliance with HF/E recommendations) did in fact bring about directly related performance times. The trend is that the more the device complies with the recommendation, the less time is required to achieve the objective of the test. In Test 4, mean performance times represent a reduction of over 75% from Condition 1 to Condition 2 (and of 54% from Condition 1 to Condition 3). Similarly, in Test 5, the mean performance times for Condition 1 versus Condition 3 reflect a reduction in performance time re-

TABLE 3

Analysis of Variance of the Results of the Laboratory Experiments

Source of Variance	*d.f.*	*Sum of Squares*	*Mean of Squares*	F
Test 1: Treatments	2	17.69	8.85	0.38
Error	27	633.84	23.48	
Total	29	651.53		
Test 2: Treatments	2	6.09	3.04	0.53
Error	27	153.63	5.69	
Total	29	159.72		
Test 3: Treatments	2	1 800.57	900.28	2.55
Error	27	9 532.03	353.04	
Total	29	11 332.60		
Test 4: Treatments	2	1 512.75	756.37	15.17*
Error	27	1 346.10	49.85	
Total	29	2 858.85		
Test 5: Treatments	2	5 902.99	2951.49	6.29*
Error	27	12 659.84	468.81	
Total	29	18 560.33		
Test 6: Treatments	2	6.68	3.34	0.83
Error	27	108.87	4.03	
Total	29	115.55		

*** Indicates significance, $p \leq 0.05$.**

quired of over 60%. Tests 1, 2, 3, and 6 exhibit similar characteristics when analyzed via *t*-tests. However, here, only Condition 1 (complete compliance) was tested against Condition 3 (complete noncompliance). The mean performance times for Tests 2, 3, and 6 also exhibited reduced time requirements for Condition 1 compared to Condition 3. The reduction was at least 20%.

In a few cases, performance times with conditions that supposedly partially complied (Condition 2) or did not comply (Condition 3) with human factors recommendations were virtually the same (Tests 1 and 2) or even numerically better with conditions assumed to be worse (Tests 1 and 4). This indicates that intuitive judgments about worse or better designs are not necessarily supported by experimental data—not a new finding!

Nevertheless, the laboratory tests clearly indicate that if a device complies with the human engineering recommendations, the time required to achieve the test objective is significantly less than the time needed with devices which do not comply with such recommendations.

FIELD TESTS

The purpose of these experiments was to validate key HF/E distress signal design principles which had been identified earlier via recommendations and in laboratory experiments, in "realistically simulated" emergencies. The experiments combined several independent variables which were previously tested separately. Thus, these experiments investigated additive or synergetic effects of distinct variables, representing the manner in which the recommendations could be used in the actual design of DS to optimize efficiency and ease of operation.

Subjects

Twenty subjects (who had not participated in the earlier laboratory experiments) took part. Ten males and 10 females volunteered and were paid $5.00 per hour for their efforts. Three of the subjects reported experience with highway flares, but none reported experience with marine signaling devices. The mean age was 23.56 yr; the standard deviation was 5.5 yr. The subjects did not know the exact purpose or hypotheses of the experiments.

Stimuli

The stimuli for the primary tasks consisted of two inert DS models. Figure 3 shows these models. Device A was approximately the size of a hand-held flare (3 cm × 25 cm). One-half of the device was cylindrical and painted red. Its end was covered by a rubber cap (similar to the "ignition cap" of actual DS), under which sand paper represented the scratch surface. The other half of the device was

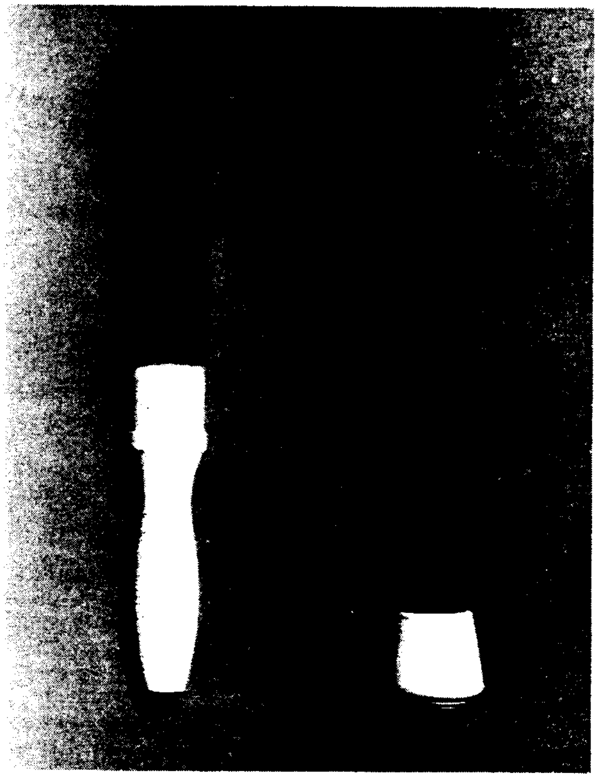

Figure 3. *Model devices used for on-water experiments.*

shaped to the hand (shape coding, such as in laboratory Test 2, Condition 1) and was painted white. The device was sealed in a plastic bag that contained a self-starter tape (sealing a cut in the bag) similar to the tape used in laboratory Test 3, Condition 1.

Device B was the same length as device A, but was cylindrical throughout, i.e., it had no shape cue for hand operation. The entire device was painted red. One end of the device had an ignition cap and scratch surface like those on device A. The other end of the device contained a similar cap with a pull chain underneath. Device B was also sealed in a plastic bag (like device A), but it did not have a self-starter tape or starter cut.

Device A combined several HF/E design recommendations (color coding, shape coding, packaging) which were individually validated in the laboratory experiments. Device B did not exhibit any of these qualities but represented conditions found in many DS. Both devices looked so realistic that the subjects were not aware that the devices were inert. Although both devices appeared realistic, they were also designed to be nonspecific. They could be interpreted as hand-held flares or smoke signals, as a combination flare-smoke, or as launchers for aerial flares.

Experimental Design

Devices A and B represented the two design conditions as independent variables. The dependent variables consisted of the performance times required to unpackage and operate devices A and B. Each subject was tested under both conditions A and B, with sex and presentation order of the independent variables counterbalanced.

Apparatus

The stimuli (devices A and B) have already been described. The other equipment used were a small inflatable rubber raft rigged to deflate as desired; a motor boat for transportation, subject observation, timing, and filming; and clipboards with elapsed time increment stopwatches. All subjects wore U.S. Coast Guard approved life vests. The experiments were performed on an inland lake in Michigan.

Procedure

All tests were performed during the summer months of 1978 on days without adverse rain or wind. The subject was taken by boat to one of two islands selected according to the wind conditions. There, the subject read standard instructions which indicated the assignment was to rate the visibility of a display which the experimenter would show from the shore. The instructions also stated that a DS was on board the raft to be used in case of an emergency. The subjects were not informed that watching and rating the display was only a secondary task designed to divert the subject's attention from deflation of the raft.

The subject then donned a life jacket and boarded the raft which was pushed out into the lake, but tethered by a 15-m rope. While the subject was observing the display, the raft deflated automatically and became limp within about 2 min, prompting the subject to activate the emergency signal (device A or B) placed in the raft. The time required for unpackaging and successfully operating the devices was recorded. Then the subject was pulled back to shore. This same procedure was followed with the second device.

RESULTS

The actual performance times are presented in Table 4. The mean performance time for device A was 0.289 min, whereas the mean time for device B was 1.376 min. The longest performance times for devices A and B were 0.67 min and 2.53 min, respectively. The shortest performance times for devices A and B were 0.10 and 0.36 min, respectively. This

TABLE 4

Results of On-Water Experiments: Performance Times in Minutes

	Device A			Device B		
Subject	*Unpackaging*	*Operation*	*Total*	*Unpackaging*	*Operation*	*Total*
1	0.16	0.05	0.21	0.90	0.56	1.46*
+ 2	0.11	0.18	0.29*	0.72	0.56	0.87
3	0.08	0.02	0.10	0.60	0.04	0.64*
+ 4	0.20	0.03	0.23*	0.81	0.11	0.92
+ 5	0.21	0.03	0.24	0.76	0.05	0.81*
+ 6	0.22	0.21	0.43*	0.20	0.16	0.36
+ 7	0.16	0.26	0.42	0.50	0.92	1.42*
+ 9	0.10	0.06	0.16	1.94	0.38	2.32*
10	0.05	0.06	0.11	0.41	0.39	0.80*
11	0.06	0.04	0.10*	0.98	0.25	2.23
12	0.15	0.10	0.25*	0.52	0.20	0.72
+13	0.10	0.12	0.22	0.44	0.54	0.98*
+14	0.36	0.21	0.57*	1.07	0.32	1.39
+15	0.31	0.13	0.44	1.90	0.63	2.53*
16	0.16	0.19	0.35*	0.32	0.41	0.73
+17	0.15	0.52	0.67*	1.02	0.82	1.84
18	0.12	0.08	0.20	1.17	0.70	1.87*
19	0.13	0.14	0.27*	2.22	0.23	2.45
20	0.18	0.08	0.26	0.42	1.72	2.14*
21	0.14	0.12	0.26*	0.66	0.38	1.04
Mean	0.157	0.131	0.289	0.878	0.468	1.376
SD	0.077	0.115	0.152	0.560	0.384	0.687

+ = Female
* = First trial

range represents much less variability for device A than for device B, in addition to the generally much shorter performance times for A than for B.

An ANOVA was done on the performance times. (The design of the analysis ignores the treatment-by-subject interactions in order to minimize the possibility of a Type I error). Table 5 presents the results of this conservative ANOVA for the times needed by the subjects to activate devices A and B. Significant differences in performance time were found for each phase of device utilization.

Discussion of the On-Water Experiments

The results indicate that the synergistic effects of the HF/E design recommendation variables applied to a DS significantly affect

TABLE 5

Analysis of Variance for the Results of the On-Water Experiments

Source of Variation	*d.f.*	*Sum of Squares*	*Mean Square*	*F*
Total				
Between Groups	1	14.82	14.82	60.0*
Error Within Groups	38	9.40	0.25	
Total	39	24.23		
Unpackaging				
Between Groups	1	5.94	5.94	31.26*
Error Within Groups	38	7.22	0.19	
Total	39	13.16		
Operation				
Between Groups	1	1.00	1.00	12.5*
Error Within Groups	38	3.14	0.08	
Total	39	4.14		

* Indicates significance, $p \leq 0.01$.

mean performance time in an on-water distress situation. The mean performance time for the unpackaging period was reduced by 83% when a self-starter was used as an aid for unpackaging, instead of having a plastic bag with no starter aid. The operation time was reduced by 70% when qualities such as shape coding, color coding, and nonambiguous design were incorporated. These simple HF/E measures reduced mean performance times 78% for the total activation (unpackaging and operation times combined) of the devices.

These significant reductions in mean performance times are due solely to the physical features of the device itself and the package, since labeling and instructions were not used for the devices. However, in the laboratory experiment, labeling and instructions were found to show significant differences.

These clear differences are even more remarkable, since each subject performed the experiments with both devices. Hence, any surprise effects in the prior test (with either device A or B) were much dampened in the second test. Still, a scrutiny of Table 4 shows that (with the exception of Subject 6) all subjects who operated device A first, and thus had become familiar with the situation, needed more time in the second test with device B. This indicates a clear performance superiority of device A.

GENERAL DISCUSSION

The results of the laboratory and on-water experiments show that a systematic HF/E design variable evaluation method is feasible and possible. One key to success is breaking down the steps of use of a DS into several distinct independent variables, for which several degrees of implementation of HF/E principles exist. Aspects of primary interest to the human factors engineer are how the operator receives basic information about the device (what it is; what it does; how to operate it) and how the operator actually manipulates (unpacks, operates) the device. In the laboratory experiments, these variables were investigated independently and then collectively under field conditions. In both experimental stages, significant reductions in performance time were found when the devices were designed according to HF/E design recommendations as compared to the original design of the distress signals. (The evaluation method used in this research may be generalized for the evaluation of many tools or machines used by an operator.)

DS constitute a special problem, as they must be designed for use by inexperienced subjects, under extremely adverse conditions, and with critical results. Current DS investigated in this research show severe shortcomings. Application of human engineering design techniques can greatly improve the performance of this operator-equipment system, often without great outlay in materials or manufacturing cost.

REFERENCES

Kroemer, K. H. E. and Marras, W. S. Human factors analysis of visual distress signaling devices. Washington, DC: U.S. Coast Guard, Report No. CG-D-84-78, for the U.S. Department of Transportation, September, 1978.

McCormick, E. J. *Human factors in engineering and design*, Fourth Edition. New York: McGraw-Hill, 1976.

McHale, E. T. Safety evaluation of distress flares and smokes. Washington, DC: U.S. Department of Transportation, Final Report No. CG-D-8977, 1977.

Miles, T. Visual distress signaling devices, Appendix H. U.S. Coast Guard Solicitation No. CG-72225-A, March 14, 1977.

Miller, J. Human factors application in boating safety. NTIS, (CG-D-90-74), AD-780-988, 1973.

MSFC-STD-267 A. Standard human engineering design criteria, September, 1966.

National Safety Council. *Accident facts 1977*. Chicago: Author, 1978.

Parker, J. F. and West, V. R. *Bioastronautics data book*, Second Edition. Washington, DC: NASA, U.S. Government Printing Office, 1973.

Pieper, A. and Cornell M. Survey of visual signalling devices and development of a testing program. NTIS, AD-A022-701, 1975.

Roebuck, J. A., Kroemer, K. H. E., and Thomson, W. G. *Engineering anthropometry methods*. New York: Wiley, 1975.

U.S. Air Force, Series 1-0. *Personal subsystem*, Second Edition. Wright-Patterson AFB, OH: Air Force Systems Command, AFSC-DH 1-3, 1972.

U.S. Army. *Human factors engineering design for army material.* Redstone Arsenal, AL: U.S. Army Missile Command, MIL-HDBK-759, 1975.

U.S. Coast Guard. Letter to the authors, dated 12 February 1979.

U.S. Department of Defense. Human engineering design criteria for military systems, equipment, and facilities, MIL-STD-1472-A, May, 1970.

Van Cott, H. P. and Kinkade, R. G. *Human engineering guide to equipment design,* Revised Edition. Washington, DC: U.S. Government Printing Office, 1972.