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Diver Performance in Cold Water

PAUL R. STANG, *U. S. Navy Deep Submergence Systems Project, Chevy Chase, Maryland*, and EARL L. WIENER, *University of Miami, Coral Gables, Florida*

Twelve experienced divers repeatedly performed several representative underwater work tasks for 90-min. sessions at water temperatures of 50°, 60°, and 70° F. Time to complete the task was the primary performance measure; choice reaction time, with mental arithmetic as loading task, and four physiological measurements were also recorded. The subjects worked in 6½ ft. of water wearing full 3/16-in.-thick wet suits and SCUBA equipment. Performance on all tasks except mental arithmetic tended to decrease as water temperature decreased. Most performance measures also showed a significant decrement over time and a significant time-by-temperature interaction. The general trend in performance measures was also reflected in several of the physiological measurements.

With the current surge in manned undersea activity comes the necessity to understand how man functions in this unique environment, so that the man-machine systems being designed for his underwater ventures can be optimized. One of the major areas in which research has been lacking (Bowen and Miller, 1967) is in the effect of cold water on a diver's working performance. To date, few quantitative data are available.

Provins and Clarke (1960) and Fox (1967) have summarized a host of literature relating to performance in cold air (Horvath and Freedman, 1947; Rubin, 1957; Teichner, 1957 and 1958; Gaydos, 1958; Gaydos and Dusek, 1958; Clark, 1961; and others). Additional studies on cold-air performance have been conducted by Clark and Cohen (1960), Lockhart (1966 and 1968) and Glickman, *et al.* (1967). Also, several studies have been reported in which subjects performed various tasks while their hands were submerged in cold water (Le Blanc, 1956; Clarke and Hellon, 1959; and Provins and Morton, 1960). Unfortunately, the results of these studies can only be used as crude predictors of the performance of a working diver, due to the vast difference between the water and air environment and the partially and totally submerged body.

A number of studies have been reported in which totally submerged divers operated in cold water; however, in most cases the temperature was not, or could not, be controlled (Cousteau, 1966; MacInnis, 1966; Bowen, *et al.*, 1966; Baddeley, 1966a and 1966b; Baddeley and Flemming, 1967; Baddeley, *et al.*, 1968; Bennett, *et al.*, 1967; Pauli and Clapper, 1967; Weltman and Egstrom, 1966). A recent study of the effect of water temperatures as low as 44° F on divers reported a definite trend toward a drop-off in performance with a lowering of water temperature (Bowen and Pepler, 1967). Most of their data, however, had to be treated qualitatively because of the small number of subjects.

Thus, very basic questions still remain to be answered. How does diver performance drop as water temperature is lowered? How is performance in cold water affected by relatively long exposures? How does performance vary from task to task, and how does work output vary over time at different water temperatures?

METHOD

Subjects

Subjects were recruited from a large population of professional, semiprofessional, and sport divers in the Miami area. All applicants were initially screened on the criteria of age (21-40 years) and diving experience (at least 40 hours using SCUBA). Those remaining were then screened on the basis of interest, mental arithmetic ability, previous cold-water experience, availability, and medical fitness.

The divers were told that the experiment involved working underwater for 90 min. each day for five consecutive days at water temperature as low as 50° F. They were offered $40 for their participation, but only if they completed the five days of experimentation. Of 60 applicants, 14 were selected. Of these, 12 completed the experiment, one stopped after the first day due to a schedule conflict, and the other was discontinued during the third day due to a headache and nausea. The following briefly summarizes the personal data collected for each diver: age in years (median 24, range 21-28), height in inches (median 71.5, range 68-74), weight in pounds (median 175, range 150-215), SCUBA experience in years (median 6.5, range 2-11), and estimated SCUBA experience in hours (median 175, range 40-5,500). All divers except one had previous diving experience in temperatures below 60° F.

Equipment

All subjects wore swimming trunks and full 3/16-in.-thick Voit neoprene wet suits. The suits, consisting of jacket, trousers, hood, and booties, were fitted to insure seals at the neck and wrists to prevent any pumping action of water in and out of the suit by body movements. Negative buoyancy sufficient to "bottom" the subjects was provided by two weight belts totaling 40 lb. A quick-release back pack held a 71.2-cu.ft. compressed air cylinder with a two-stage, single-hose, Sportsways Malibu regulator and Sea-Vue air gauge. Subjects wore their own face masks, but all other equipment was furnished by the experimenter. One-way communication was maintained with the divers through a small earphone placed inside their hoods.

The experiments were carried out at a depth of 6.5 ft. of fresh water in a plywood and fiberglass tank 8 ft. high and 5 ft. square. Subjects knelt on the floor of the tank and performed the tests on a specially constructed 24-in.-high workbench frame rigidly attached to the tank. A 10-X-10-in. viewing port permitted observation of the diver at all times. A constant water flow of 4 gal/min was maintained and the water temperature was controlled to ±1° F by use of a refrigeration unit in the circulation system. Water clarity and illumination were maintained at a constant level, providing excellent visibility.

Tasks and Physiological Measurements

Table 1 gives a brief description of the physiological measurements which were taken and the six tasks which were selected to be representative of underwater work at a low activity level. These are described in detail below.

TABLE 1

Description of Tasks, Physiological Measures, and Their Units of Measure

Task or Measure	*Description*	*Units*
Assemble Base Plate	Simple assembly–attaching plate to work bench frame with wing nuts	sec.
Torque Bolt	Full arm motion–loosening torqued nuts and bolts with wrenches	sec.
Speed Wrench	Full arm motion–removing bolts with speed wrench	sec.
Assemble Screw Plate	Simple assembly–attaching two plates together, one of which is first secured to work bench with wing nuts	sec.
Screw Plate	Fine digital motion–transferring small nuts and screws from one side of plate to the other	sec.
Choice Reaction Time	Two-choice reaction–used as primary task with mental arithmetic as "loading" task	millisec.
Mental Arithmetic	Adding and subtracting integers–used as "loading" task with reaction time as primary task	errors
"V" Test	Two-point tactile discrimination–used as measure of finger numbness	gap (1/64 in.)
Air Consumption	Measure of air inhaled by divers	psi
Mean Skin Temperature	Average temperature of three points on body	°F
Oral Temperature	Measure of drop in oral temperature	°F

Assemble-base-plate, torque-bolt, and speed-wrench tasks. In the assemble-base-plate task, the subject was timed while he took a plate (described below) off a rack on the left side of the workbench frame and positioned it on four posts, then screwed on two wing nuts to secure it to the bench. In the torque-bolt task, the object was to loosen 12 pretightened (500 in/lb) nuts and bolts on the left side of the base plate with a 10-in. socket wrench on the nut and an 11-in. box wrench on the bolt. The subject merely loosened the bolts and nuts but did not remove them. In the speed-wrench task, the subject removed twelve 1.5-in.-long hand-tightened hex bolts on the right side of the base plate using a 15-in. speed wrench with a 3.5-in. throw. The task was completed when he had removed all bolts and deposited them in a box attached to the workbench frame.

All three of these tasks employed an aluminum plate, 19 X 14 in., which was designed to be secured quickly and firmly to the workbench frame. Three-by-six-inch grids of 12 holes were drilled on both the left and right sides of the plate to accept the 0.5-in.-diameter bolts used in the torque-bolt and speed-wrench tasks.

Assemble-screw-plate task. In the assemble-screw-plate task, the subject removed a plate from a rack on his right and positioned and secured it to the workbench frame in the same manner as in the assemble-base-plate task. He then took a screw plate from another rack on the workbench frame and secured it to the plate in a vertical position. The screw plate was designed according to specifications given in a previous experiment (Bowen and Pepler, 1967).

Screw-plate-task. The screw-plate task consisted of removing eight 3/4-in.-long, USS No. 10-24, slotted, round-head, brass machine screws and hex nuts from the upper half of the plate and attaching them in the corresponding holes on the lower half.

Choice-reaction-time task. A two-choice reaction-time task as the primary task, with simple mental arithmetic as a secondary or "loading" task, was designed to simulate heavy perceptual loading. A small metal box with two lights (9/16-in.-diameter white bulbs) side by side and 2.5 in. apart was mounted outside a special viewing window directly in front of the subject. Subjects responded by pressing one of two pushbutton switches mounted in a hand-held box. The mental arithmetic utilized combinations of four one-digit integers (a, b, c, d) which were selected randomly with the following limitations: $a > 0$, $b > 0$, $c > 0$, $d > 0$; $10 \leqslant a + b + c \leqslant 20$; $5 \leqslant a + b + c - d \leqslant 15$; and $a + b + c - d \neq 10$. The subject was to perform the operation $a + b + c - d$ mentally and indicate whether the result was above 10 by pointing the thumb of his nonpreferred hand up, or below 10 by pointing down. Twelve blocks of 15 combinations of numbers were recorded on tape. There was a 10-sec. interval between the beginning of each of the combinations in a block. Ten seconds before the beginning of a block a warning was given and, for each combination in the block, the word "ready" was given followed in 1-sec. intervals by the four digits. The subject was required to give a thumb signal before the start of the next combination. Between b and c of each set, one of the lights, chosen randomly, was illuminated and the subject's reaction time was recorded in milliseconds on a Hunter Klockounter. This test lasted 2.5 min., during which one of the blocks, selected randomly, was played and the mental-arithmetic and reaction-time responses were recorded.

Mackworth "V" test. A Mackworth "V" test, similar to that used in several previous experiments (Mackworth, 1953; Provins and Morton, 1960; Bowen and Pepler, 1967), was employed to measure finger numbness. The apparatus contains pairs of ridges with gaps varying in 1/64-in. increments. While the subject was standing in the tank, an experimenter pressed the first pad of the subject's left index finger at random points on the test apparatus, just below the water's surface. The subject responded with his right hand by indicating whether he felt one or two edges. This process was continued until the location of the just-discriminable gap was determined. To assure uniformity of measurement, the same experimenter always administered the test.

Air consumption. Air consumption was measured every 15 min. by reading an air gauge attached to the subject's breathing apparatus. Readings were accurate to ± 15 psi.

Oral and skin temperature. Oral and skin temperatures were taken on seven of the subjects. Oral temperature recorded to ± 0.1° F was measured before the subject donned his wet suit and as soon as he emerged from the water at the end of each session. In each case, he kept the thermometer in his mouth for five minutes before a reading was taken. Skin temperatures at three body locations were monitored on a Honeywell potentiometer to ± 1° F by attaching 24-gauge iron-constantan thermocouples at (1) the upper portion of the lateral aspect of the left arm at the junction of the biceps and the tendon of insertion of the deltoid, (2) the lateral aspect of the upper portion of the lower left leg over the head of the fibula, and (3) the anterior of the right thigh at scrotal level. The mean of these three temperatures, mean skin temperature, has in the past provided a good approximation of the body's average skin temperature (Glickman, personal communication).

Experimental Design

All subjects were run under all experimental conditions. A diver entered the tank at the same time on five consecutive days. While submerged each day for 91.5 ± 6.5 min. (plus setup and tear-down time), he performed the complete set of seven tasks every 15.25 ± 3.5 min. Thus, six sets of tasks were performed during each session. Setup (4 ± 1 min.) consisted of arranging the plates and tools in their proper place before the day's session began. In tear-down (4 ± 1.5 min.), the diver handed the plates and tools out of the tank at the end of the session. The torque-bolt, speed-wrench, screw-plate, reaction-time, and Mackworth "V" tests were selected in a balanced randomized order with the assemble-base-plate task always preceding the torque-bolt task or the speed-wrench task (whichever came first) and the assemble-screw-plate task always preceding the screw-plate task. Air consumption was measured at the end of each set, and three mean skin temperature readings were taken during the set and averaged later.

The first two sessions were conducted at 60° F for task familiarization only. The results reported are based on the last three days at 50°, 60°, and 70° F, presented in a balanced randomized design which consisted of having 2 of the 12 subjects run in each of the six possible orders. For the low activity level, and duration of exposure, these temperatures were selected to be representative of a comfortable condition (70° F), a moderately cool condition (60° F), and a cold condition (50° F) customarily encountered by working divers.

Procedure

In the first session, the diver's personal data were recorded, and he then listened to a 9-min. tape recording of instructions while an experimenter demonstrated the tasks and procedures. Emphasis was placed on the importance of developing and maintaining a consistent working procedure and operating at maximum capacity for all sessions. Oral temperature was taken and the subject's three thermocouples were attached. After donning his wet suit and SCUBA equipment, he climbed into the tank and arranged the tasks and tools, and then signaled that he was ready to begin. The end point of each task was signaled by the experimenter, and the diver was told which task was next, and so on, for the duration of the dive. At the end of the day's session, his oral temperature was taken and he proceeded directly to a hot shower.

RESULTS

Figure 1 shows performance over time at each of the three temperatures for all the measures taken except mental arithmetic and oral temperature. Table 2 shows the means for all the tests except mental arithmetic. It also shows the percent drop in performance between the 70°-F and 60°-F conditions, and between the 60°-F and 50°-F conditions. Table 3 shows the results of the analyses of variance. Each analysis was essentially a subjects-by-treatments design, with each main effect and each interaction of main effects tested against its respective interaction with subjects. No significant difference ($p < .05$) between temperatures was found by a χ^2 test on the number of errors in the mental arithmetic (see Table 4). Temperature, set, and temperature-by-set interaction effects were found to be significant ($p < .01$) for most of the tasks and physiological measurements.

DISCUSSION

All primary tasks and physiological measurements showed a significant difference in performance for the three temperatures used. This is in agreement with the expectations of several professional divers interviewed prior to the study and with the data of Bowen and Pepler (1967). The screw-plate task, which required the finest degree of manual dexterity, showed the largest decrement in performance (40.7% for the 60°-to-50° drop) which was about twice as great as that shown by Bowen and Pepler's preliminary experiment with the same screw plate. Their divers, however, were exposed for a considerably shorter period, which might account for the smaller drop.

There was also a significant drop in perform-

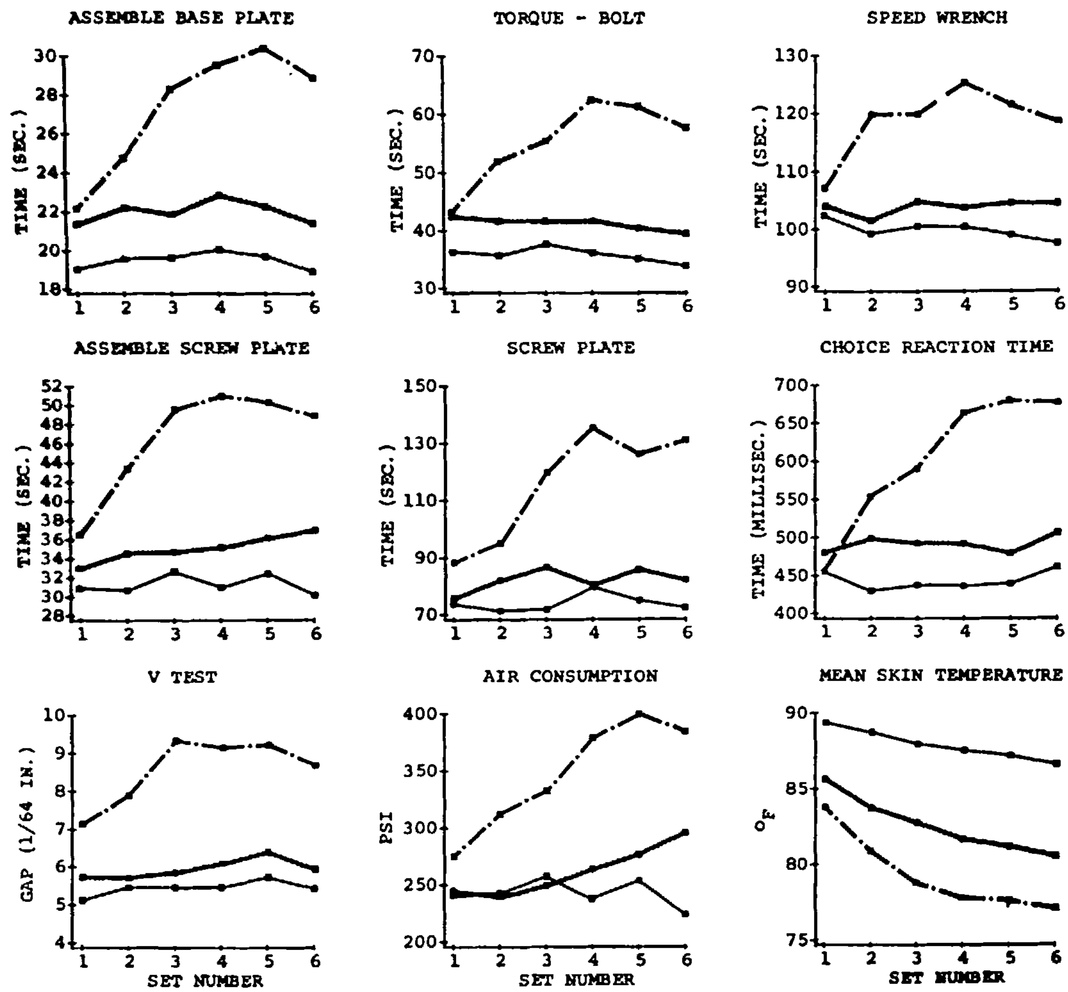

Figure 1. Performance measures versus set number for all tasks at 50° (——·——), 60° (———), and 70° (———). Each task (or measure) was performed once during each set. Each set had a duration of 15.25 min.; therefore, the six sets represent a total exposure of 91.5 min.

TABLE 2

Means Measures for Each Session

Task or Measurement	N	Practice Sessions at 60° F: 1st	Practice Sessions at 60° F: 2nd	Main Experimental Sessions: 50° F	Main Experimental Sessions: 60° F	Main Experimental Sessions: 70° F	% Drop 70°→60°	% Drop 60°→50°
Assemble Base Plate (sec.)	12	26.4	23.7	27.3	22.0	19.6	12.1	24.4
Torque-Bolt (sec.)	12	58.1	47.5	55.3	41.0	35.7	14.8	34.8
Speed Wrench (sec.)	12	113.7	110.0	118.7	103.8	99.9	3.9	14.4
Assemble Screw Plate (sec.)	12	39.9	38.1	46.7	35.1	31.4	11.8	32.9
Screw Plate (sec.)	12	98.4	88.2	116.2	82.6	74.3	11.1	40.7
Choice Reaction Time (msec.)	12	648.3	518.5	603.6	490.5	443.9	10.5	23.0
"V" Test (gap in 1/64 in.)	12	5.9	6.3	8.6	5.9	5.5	8.4	44.4
Air Consumption (psi)	12	354.2	301.5	347.4	261.3	247.8	7.6	33.0
Mean Skin Temperature (°F)	7	83.5	83.0	79.3	82.7	87.9	6.0	4.0
Oral Temperature (°F)	7	2.96	3.56	4.27	3.86	1.97	95.9	10.6

Notes: Means were taken for M·N observations, where M = six sets per session and N = the number of subjects. For oral temperature, M = one reading taken per session.

"% Drop 70° → 60°" is the percent drop in performance from the 70°-F session to the 60°-F session.

"% Drop 60° → 50°" is the percent drop in performance from the 60°-F session to the 50°-F session. A drop in performance is actually an increase in the dependent variable for all the tasks and physiological measures except mean skin temperature and oral temperature.

ance ($p < .01$) during the 90-min. exposure for all measures except torque bolt and speed wrench. The experimenter noted that the divers seemed to be using these two tasks, especially the speed wrench, as vigorous exercise to keep warm. This was also confirmed by a slight rise in mean skin temperature during these tasks. With the exception of the assemble-screw-plate and oral-temperature measures, all measures also showed a significant set-by-temperature interaction ($p < .01$). For the 50°-F sessions, all the tasks showed a pattern (see Figure 1) in which performance dropped off at a fast rate initially, then tended to level off or even increase near the end of the session. This trend is also seen in the air-consumption, "V," and mean-skin-temperature measurements. The reason for the leveling or increase is not known conclusively, but comments from the divers indicate that near the end of the session there was a definite anticipation of escaping the cold water, which could account for their apparent "end spurt." The explanation for air consumption following the same pattern as the tasks may be in its relation to the diver's body heat balance.

Hong and Rahn (1967) have shown that oxygen absorbed is directly related to the body's heat production and, although air consumption may not be directly related to oxygen absorbed by the body, it can be used as a crude approximation. For a wide range of activities, the correlation between oxygen absorption and air consumption data from Waite (1966) was found (by the present authors) to be 0.999. If such a correlation holds for this experiment, the divers were experiencing a large thermal imbalance during the 50°-F exposure. Another contributing factor to the increased air consumption may lie in the common belief among divers that air consumption is an index of the stability or "steadiness" of a diver. A buildup of stress in a diver experiencing hypothermia might then cause mounting anxiety and a consequent increase in air consumption. This thermal imbalance is also indicated by the drop-off of mean skin temperature (see Figure 1). It is interesting to note that the 70°-to-60° drop is slightly larger than the 60°-to-50° drop, which was not expected.

Unfortunately, it was not convenient to record rectal temperatures. The drop in oral temperature was measured but, because the subjects were breathing through a mouthpiece, it could not be used to indicate deep-core body temperature. The oral temperature however,

TABLE 3

Analysis of Variance of Dependent Variables

Source	df	MS	F	MS	F	MS	F
		Assemble Base Plate		*Torque – Bolt*		*Speed Wrench*	
Subjects (A)	11	209.59		2,969.45		4,324.47	
Temperatures (B)	2	1,130.75	43.10**	7,366.56	27.57**	7,114.44	13.72**
A X B	22	26.23		267.24		518.45	
Sets (C)	5	60.26	7.12**	153.71	1.45	155.63	1.41
A X C	55	8.46		106.34		82.18	
B X C	10	35.62	3.30**	230.04	2.58**	195.85	2.87**
A X B X C	110	10.80		89.04		68.29	
Total	215						
		Assemble Screw Plate		*Screw Plate*		*Choice Reaction Time*	
Subjects (A)	11	581.13		782.05		379,584.68	
Temperatures (B)	2	4556.91	62.68**	35,460.06	73.33**	485,460.00	6.95**
A X B	22	72.70		483.59		69,891.57	
Sets (C)	5	204.98	3.88**	2,134.01	13.36**	33,728.90	3.95**
A X C	55	52.86		159.68		8,530.66	
B X C	10	105.40	1.59	1,373.38	6.50**	31,381.20	3.51**
A X B X C	110	66.29		211.31		8,942.20	
Total	215						
		"V" Test		*Air Consumption*			
Subjects (A)	11	38.67		67,451.36			
Temperatures (B)	2	201.20	33.10**	224,328.25	77.93**		
A X B	22	6.08		2,878.74			
Sets (C)	5	5.73	7.56**	17,317.45	13.79**		
A X C	55	0.76		1,255.79			
B X C	10	2.22	2.79**	9,286.00	6.28**		
A X B X C	110	0.80		1,478.35			
Total	215						
		Mean Skin Temperature		*Oral Temperature*			
Subjects (A)	6	91.39		11.69			
Temperatures (B)	2	788.74	73.77**	10.52	22.22**		
A X B	12	10.69		0.47			
Sets (C)	5	69.61	76.75**				
A X C	30	0.91					
B X C	10	4.82	8.69**				
A X B X C	60	0.56					
Total	125						

**$p<.01$

TABLE 4

Contingency Table for Mental Arithmetic Errors Showing the Number of Subjects Above and Below the Median Number of Errors

Errors	*50° F*	*60° F*	*70° F*
≤3.0*	5	8	6
>3.0*	7	4	6
Totals	12	12	12

Note: 3.0 is the median of the number of errors for the subject-set sums. $\chi^2 = 1.56, df = 2$.

did show some surprising results. The 70°-to-60° drop was unexplainably large relative to the 60°-to-50° drop.

The mental arithmetic had the greatest variance of all the measures taken. It did not successfully meet the criterion for being a heavy loading task which was sensitive to temperature changes. The divers' comments indicated that in any of the sessions, even a momentary lapse in concentration resulted in errors. So, the authors agree with the current view that complex and perceptually demanding tasks will suffer considerable performance losses due to low water temperatures. These conditions, however, are difficult to simulate.

In summary, the results showed a definite effect of cold water on both the tasks and physiological measurements administered. The subjects were able to operate at 50° F for 90-min., but a large decrement in performance was experienced. Grosser movements were less affected than finer movements by the cold, and simple assemblies employing both gross and fine movements were only moderately affected. The data of the physiological measures showed the same general pattern as the data for the performance tasks used.

We believe that auxiliary heat supplied to the body will be necessary to enable divers to perform effective work during prolonged dives in water temperatures below 60° F. Ocean project planners, anticipating underwater work, should give considerable thought to the temperatures in which the divers will be operating, the thermal protection required, and the tasks to be accomplished before sending divers on difficult or hazardous missions.

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