BOOZ • ALLEN APPLIED RESEARCH, INC.

A REPORT ON A STUDY OF PERSONNEL FLOTATION DEVICES

For

U. S. Coast Guard
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TABLE OF CONTENTS

INDEX OF FIGURES

INDEX OF TABLES

I. INTRODUCTION

1. SCOPE OF STUDY

The purpose of this study was to analyze the performance requirements of personnel flotation devices, to survey and evaluate the state of technologies related to personnel flotation devices, and to make recommendations based on the preceding activities.

Emphasis was placed on the problems and requirements for personnel flotation devices in recreational boating. Problems more closely related to personnel aboard merchant vessels or ships for hire, such as antiexposure and search and rescue aids, were not considered in this study. The reason for this emphasis was that both the total number of fatalities and the rate of increase in facilities related to recreational boating far exceeded those related to any other area.

2. METHOD OF APPROACH

This study employed two different approaches. The first was to develop analytic models, based on available data and/or logic, to determine the performance requirements of personnel flotation devices. The second was to gather information through meetings with a considerable number of manufacturers, producers, and distributors of flotation devices; to survey the current state of technologies; and to develop estimates of factors influencing the purchase and wear acceptance of personnel flotation devices.

The methodology used in the analysis was to develop separate models for each performance requirement and to consider the characteristics of personnel flotation devices parametrically, so that both the absolute and relative effects of each characteristic upon a performance requirement could be established. The analyses related to buoyancy and body orientation were separated from those concerned with wear acceptancc and the assessment of effectiveness. This was done because the analysis of wear acceptance was based on data far less precise than those used to evaluate buoyancy and orientation. The intent was to construct a series of independent models to analyze successively the effects of certain major personnel flotation device factors upon buoyancy, achieved body orientation, wear acceptance, short-term likelihood of survival (excluding the effects of exposure), and long-term likelihood of survival (including the effects of water exposure). The final results were an estimate of the absolute effectiveness of different personnel flotation device configurations having different characteristics, and estimates of the relative effects of the different personnel flotation device factors upon the likelihood of survival.

The assessment of the state of technology was based partly on the results of the requirements analysis and partly on the survey of materials and designs for personnel flotation devices. No effort was made to evaluate specific manufactured personnel flotation devices; the evaluation was restricted to types of designs. The assessment of buoyant materials consisted of two evaluations; in the first, candidate materials were screened with respect to basic safety factors; in the second, materials were rated with respect to their contribution to an effective personnel flotation device.

The capability of manufacturers of personnel flotation devices to absorb the costs of research, development, and testing (RD&T) was analyzed on the basis of estimated manufacturing costs, price structure, and the increase in sales price necessary to amortize the RD&T costs.

Finally, the study was reviewed to assess what future activities should be performed by the U. S. C. G. to enhance water safety.

3. ORGANIZATION OF THIS REPORT

This report is divided into two parts, the first of which contains six sections:

- Introduction
- Personnel Flotation Device Requirements
- Trade-Off and Effectiveness Study
- State-of-the-Art Assessment
- Cost Analysis
- Conclusions and Recommendations.

The second part consists of an appendix containing the supporting data, models, and a list of visits made.

II. PERSONNEL FLOTATION DEVICE REQUIREMENTS

1. SUMMARY

A series of studies was conducted to determine the performance requirements for personnel flotation devices. These studies initially consisted of analyses to determine the following:

- The need for flotation assistance
- The amount of flotation assistance required
- The requirements for the personnel flotation device to orient the person's body in a safe attitude
- The capability of a range of configurations of jacket-type personnel flotation devices to meet the attitude-achieving requirements
- The requirements for throw-type personnel flotation devices.

In a number of the studies performed, simplifying assumptions were made or idealized conditions were examined. All conclusions reached must be tempered by this fact, and firm judgments should be deferred until validating water tests are performed.

(1) Requirement for Flotation Assistance

There were approximately 1200 recreational boating fatalities in the year 1966. From 1963 to 1967, there was a 21-percent increase in this type of fatality. In comparison, there were slightly over 200 fatalities related to commercial craft in 1966, with a 7-percent increase since 1963. These data clearly show the seriousness of the risks associated with boating. Statistics show that the average American is a poor swimmer. It is estimated that he can swim an average of about 75-100 feet, or stay afloat for about 1 to 1-1/2 minutes. Clearly, there is a need for personnel flotation assistance for any person who enters the water accidentally.

(2) Buoyancy Requirements

The current United States Coast Guard requirement of 16 pounds of buoyancy for a buoyant vest is inadequate for the adult population. It is estimated that 22 pounds of buoyancy should be provided for any jacket for an adult. This would provide sufficient buoyancy for 95 percent of the adult population. This requirement is essentially independent of the user's body weight.

(3) Body Orientation Requirements

The natural body attitude in water is approximately 30 degrees, face down. In this position, the face is under water. The mouth and nose of an unconscious person are not clear of the water until the body is at an angle of somewhere between 15 and 45 degrees, inclined backward from a vertical position in the water. Therefore, the body must be inclined at an angle of approximately 30 to 60 degrees backward to ensure sufficient freeboard to keep the mouth and nose out of choppy water. A personnel flotation device should be capable of rotating the body to this attitude from any initial orientation.

(4) Location of Buoyant Material

Buoyant material for an adult personnel flotation jacket should not be attached to the back of the wearer unless it is necessary to support the head and is free-floating. The effect of buoyant material located on the person's back is to induce forces that tend to keep the person in a face-down orientation. Buoyant material located on the front of the person should be placed as high on the chest as possible to assist in achieving a safe attitude. Any material located more than approximately 10 inches below the shoulders has a detrimental effect on the ability to achieve a safe attitude.

(5) Shape of Buoyant Material

As previously noted, buoyant material should be as high as possible to assist in achieving a safe attitude. Any shape that is sculptured to enhance ease of movement by reducing the amount of material located on the upper chest has a detrimental effect on the ability to achieve a safe attitude.

(6) Thickness of Buoyant Material

The required thickness of buoyant jacket material depends on both the necessary buoyancy and the forces necessary to achieve a safe attitude. In almost all configurations examined, which did not employ straps, an average thickness of between three and five inches of material was required to permit achievement and maintenance of the necessary orientation from a face-down position. When straps were used up to five inches was required.

(7) Density of Buoyant Material

The density of the buoyant material has relatively little effect upon the attitude-achieving capability of a personnel flotation device. However, once the body is oriented backward, the density of the material can significantly affect the resulting achieved attitude: in general, the lighter the material, the farther back the body will stabilize. Configurations of the materials with the same thickness but different densities will, of course, have different buoyancies; therefore, other factors being equal, it is a distinct advantage for a personnel flotation device to be constructed of the lightest possible material. Other factors that must be considered are the reliability of the buoyant material and its stiffness, which affects the user's comfort and ease of movement.

(8) Strap Effects

Straps on the buoyant material have two primary purposes:

1. To keep the jacket from shifting from its designed position on the body to a higher position when in water. Such a shift would decrease the freeboard between the face and the surface of the water.

2. To locate the exact position of the buoyant forces, which will act through a point on the strap. This would alter the location of the acting buoyant forces to a point farther up on the chest which is highly desirable with respect to achieving a safe attitude.

2. REQUIREMENT FOR FLOTATION ASSISTANCE

Two different approaches demonstrate clearly the need for flotation assistance for people who have accidentally entered the water. The first approach is a review of statistics and projections of drownings, while the second is an examination of the need based on the swimming abilities of the general American population.

(1) Statistics and Projection on Drowning

During the period 1963 to 1966, the number of drownings steadily increased at an average rate of 6 percent per year, mainly as a result of the increase of small boat ownership. As indicated by Figure II-1, drownings from commercial craft have been increasing by some 7 percent, while drownings from recreational craft have increased by 21 percent.

A recent survey sponsored by the Department of Interior (Bureau of Outdoor Recreation) indicates that the frequency of participation in boating, as well as other water sports, is on

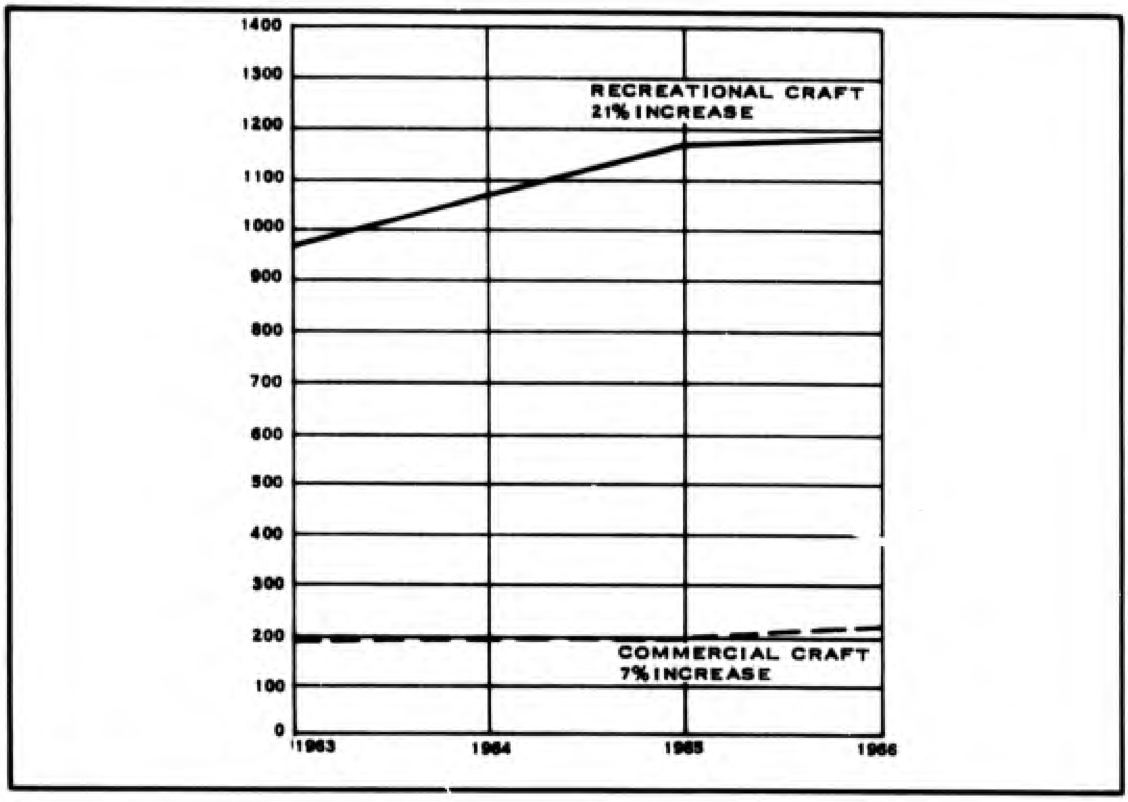
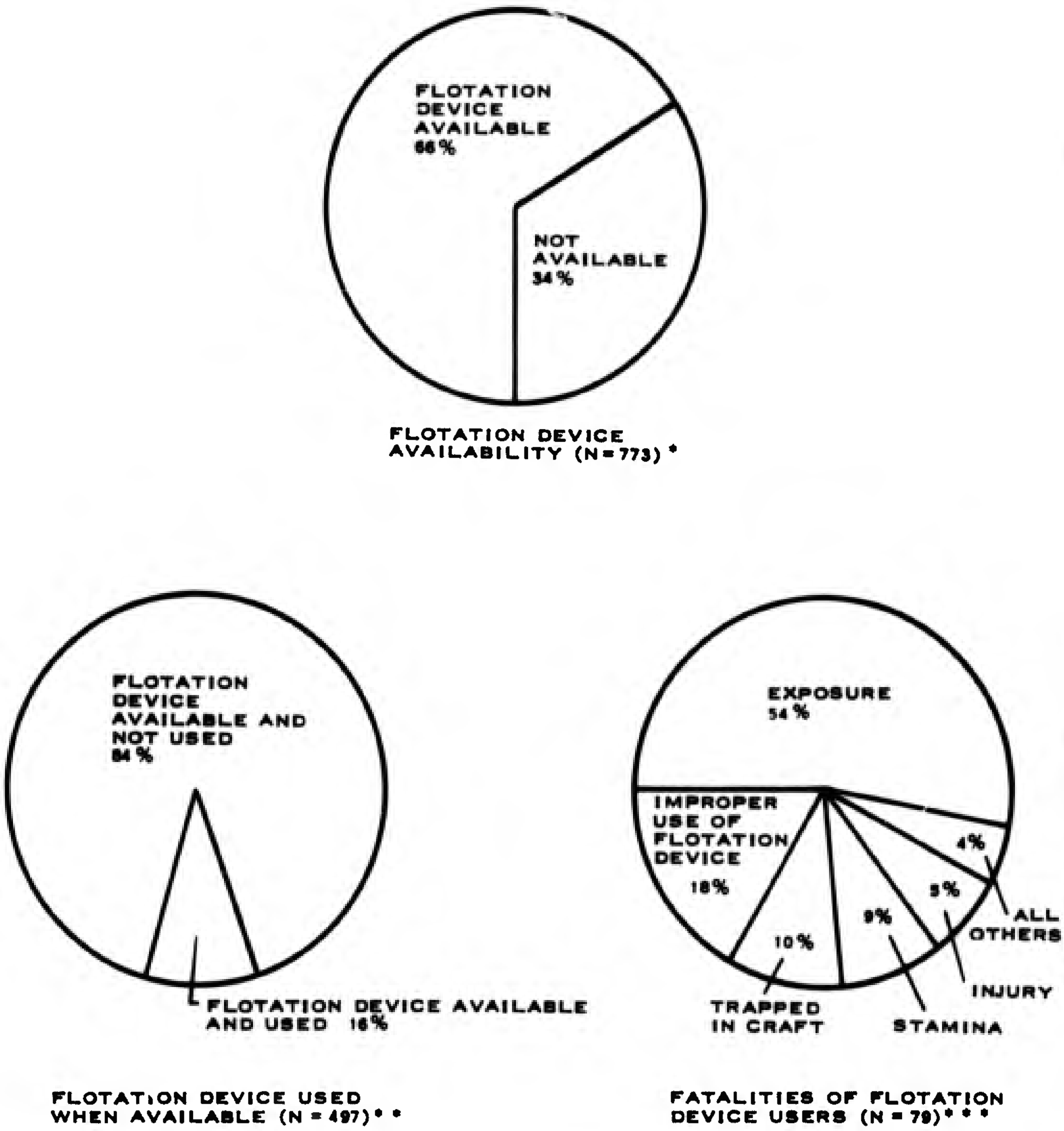


FIGURE II-1. Water Fatality Trends for Recreational Water Sports

the rise. Based on the figures in terms of numbers of boating occasions, predictions for 1980 and 2000 indicate increases of 76 and 215 percent respectively. It is clear, therefore, that considerable emphasis must be placed on the recreational aspects of any study addressing lifesaving device requirements.

An examination of the details of lifesaving device factors with respect to recreational boating fatalities reveals a number of problem areas. According to the Boating Statistics Report of the Coast Guard in 1967 (see Figure II-2), flotation devices were not available in 34 out of 100 drowning cases; and they were not used, even though available in 85 cases out of 100.



* FOR 773 CASES, A DEFINITE ANSWER TO THE QUESTION "WAS A LIFE SAVING DEVICE AVAILABLE" COULD BE DEFINITIVELY ANSWERED "YES" OR "NO"; FOR AN ADDITIONAL 345 CASES THE ANSWER WAS "UNKNOWN".

* * FOR 497 OF THOSE 773 CASES, THE ANSWER WAS "YES", THE DEVICE <u>WAS</u> AVAILABLE."

* * * FOR 79 CASES OF THOSE 497 CASES, THE DEVICE WAS AVAILABLE <u>AND</u> USED, BUT THE USER DROWNED.

FIGURE II-2. Relationships Among Personnel Flotation Device Availability, Use, and Fatalities

However, an adequate device does not ensure survival, especially if the user is not familiar with it or if weather conditions are severe. In 1967, for those who did use a flotation device, improper use and exposure resulted in 56 fatalities out of a total of 79 cases.

Nevertheless, survival rate was approximately 60 percent with a flotation device as compared to approximately 30 percent without a flotation device(based on an average for the period 1962 to 1965) as reported in the Coast Guard Recreational Boating Report, "Survival of Persons in Peril in Fatal Accidents"). A more detailed review of the literature on lifesaving, statistics of recreational boating, and relevant human factors data is presented in Appendix A.

(2) Swimming Ability of the General Population

A person aboard a vessel always risks entering the water because of an accident. An American Red Cross survey of fatalities in public waters in the Washington, D.C. area during the years 1945 to 1967 indicated that the greatest percentage of all drownings whose causes could be determined involved small boats. About 45 percent of these drownings were associated with the capsizing of a small boat, while 30 percent involved falls from the craft.

A study of 16,000 military personnel, conducted in 1946, demonstrated that the average American is a poor swimmer.[(1)] It was shown that about 10 percent could not swim at all, about 25 percent could not swim 50 feet, and about 50 percent could swim 50 to 100 yards. It is estimated that normal swimming capability is reduced by half when the swimmer is clothed and in cool, choppy water; this means that the average swimmer would be capable of swimming 75 to 100 feet under these conditions. Furthermore, the average subject in the referenced study could float or tread water for only about 1-1/2 minutes. Figure II-3 presents an estimate, based on this study, of the probability of survival of persons who enter the water accidentally and without a flotation device.

A personnel flotation device, to be effective, must not only provide buoyancy and a safe, stable attitude, but should also be available at the time of need. If it is intended to be worn by a person, it must be an acceptable article of apparel to that person. Unfortunately, most devices that appear to provide all safety requirements are not highly acceptable or wearable. Therefore, an analysis was made to define the wear-acceptance factors of a jacket-type personnel flotation device and to evaluate the previously mentioned configurations with respect to these factors in order to estimate their availability. The availability of a personnel flotation device thrown to an immersed person depends primarily upon the distance the device must be thrown, the accuracy of the throw, and the swimming ability of the immersed person. An analysis of devices to be thrown was made to estimate their availability. The probability of survival for each type of device was established on the basis of the product of the estimated survival likelihood for the device and its availability.

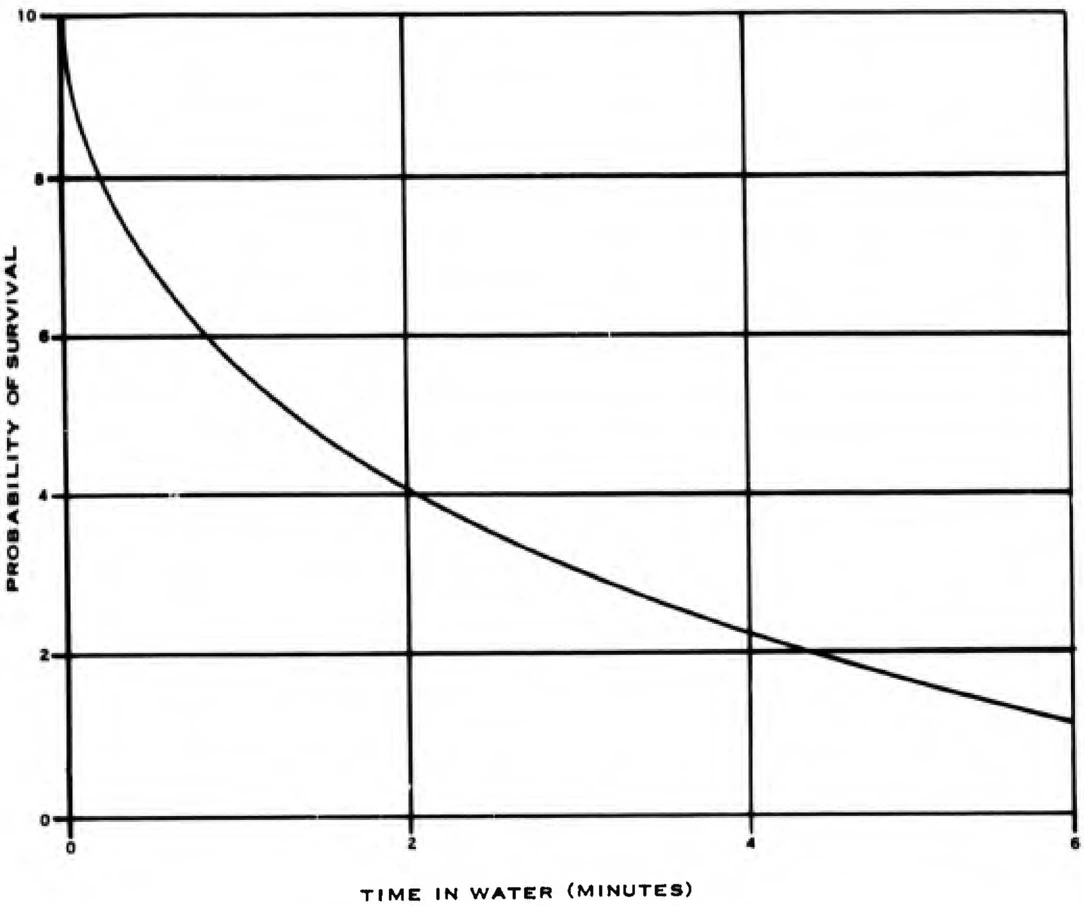


FIGURE II-3. Probability of Surviving Without Flotation Assistance

3. BUOYANCY REQUIREMENTS

A personnel flotation device should provide sufficient buoyancy to keep the head and neck of the immersed person out of the water. No clear requirement for additional buoyancy has been demonstrated (some British studies suggesting an additional requirement appear inconclusive), except where waves are small, irregular, or choppy, and therefore likely to wash over the head of the immersed person. While waves tend to be sinusoidal in form, they are not uniformly so; irregularities and perturbations occur, and these cause choppiness. Since there are insufficient data to develop a creditable model of wave characteristics applicable to the smaller waves, this study excluded their effects on the buoyancy requirements for personnel flotation devices.

Empirical data were used to determine the buoyancy requirements of children and adult males. As anticipated, there was no clear relationship between buoyancy requirements and adult body weight. Figure II-4 is a scattergram of the empirically derived data and shows the buoyancy requirements as a function of body weight.[9] The data were derived from tests, apparently in fresh, still water, by Mellon Institute.

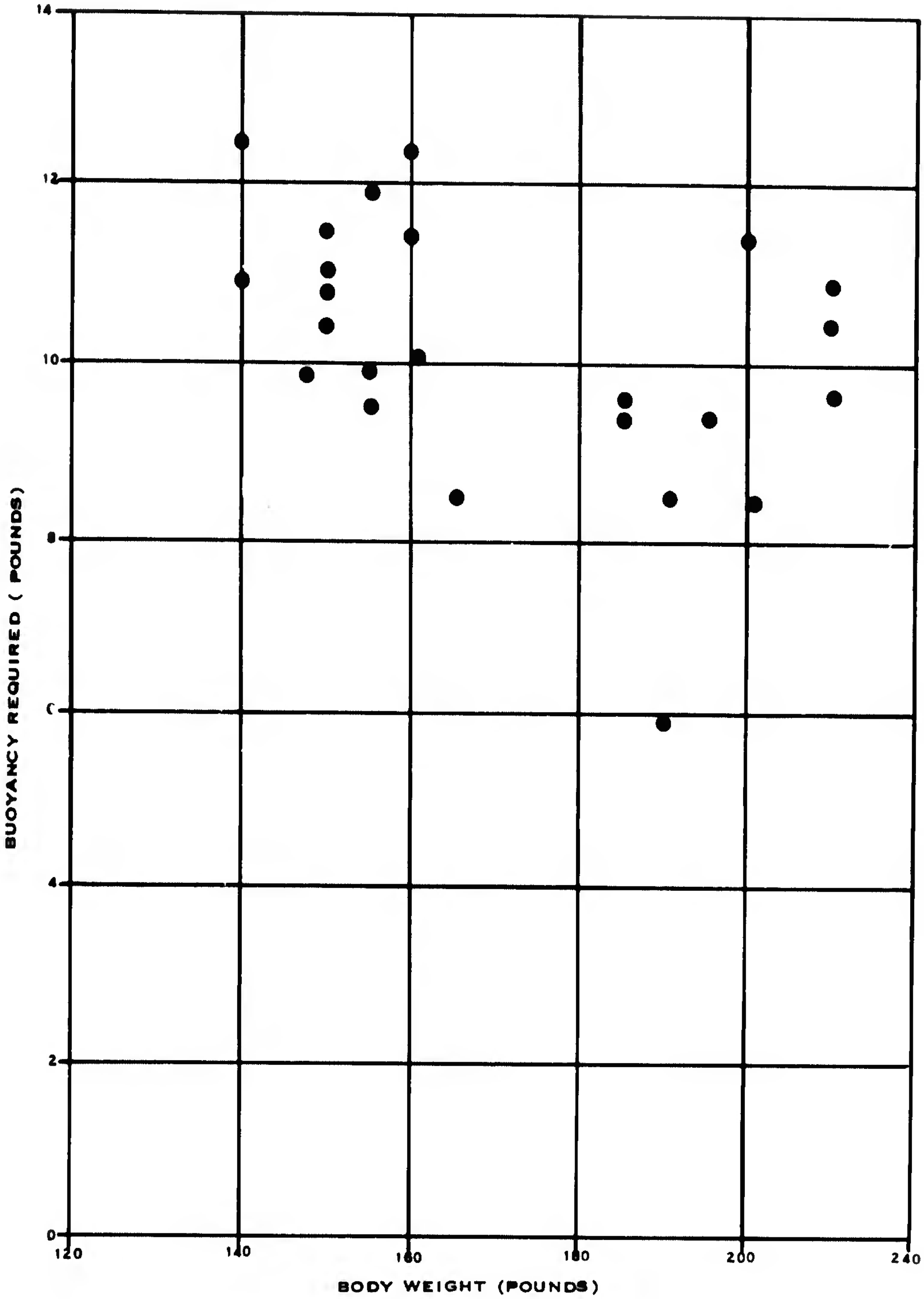


FIGURE II-4. Buoyancy Requirements for 23 Adult Males

The basic buoyancy requirements for various percentages of the general population were calculated on the basis of the previously mentioned data. These requirements should be increased to compensate for the effects of clothing and panic/exertion.

(1) Effect of Clothing

Several pounds additional weight should be added to the body weight to account for clothing. No data were obtained on the weight of typical recreational clothing; however, for the purposes of this study, five pounds was assumed to be a reasonable added requirement.

(2) Effects of Panic/Exertion

Panic or exertion can cause an increased rate and depth of breathing. The increased exhalation volume results in a loss of body buoyancy. This can produce a change in buoyancy requirements of one to two and one-half pounds.

The buoyancy required to support 99 percent of all adult males, without clothing and not under exertion, is 17 pounds. Fifteen pounds of buoyancy is sufficient for 95 percent of the adult males. When a safety factor is added for clothing and the effects of exertion, 24.5 pounds is needed to support all but one percent of the adult males, while 22. 5 pounds is required to support all but the top five percent of the adult male population. Figure II-5 shows the buoyancy requirements for children,[3] drawn from a recent Japanese study, while Figure II-6 shows the buoyancy requirements for adults, as calculated on the basis of the Mellon study.[9]

Note that there is a discrepancy between the results obtained for children and those obtained for adults. The buoyancy requirements for children appeared to vary directly with their body weight, but there was no apparent relationship between adult buoyancy requirements and body weight. Japanese children were used in the buoyancy tests on children; it is not known whether similar results would be obtained with American children.

4. BODY ORIENTATION REQUIREMENTS

An analysis was made of the general requirement for personnel flotation devices that would not only provide the needed buoyancy but also maintain the immersed person in a safe position. In addition, analyses were conducted to determine the specific attitude-achieving requirements of personnel flotation devices.

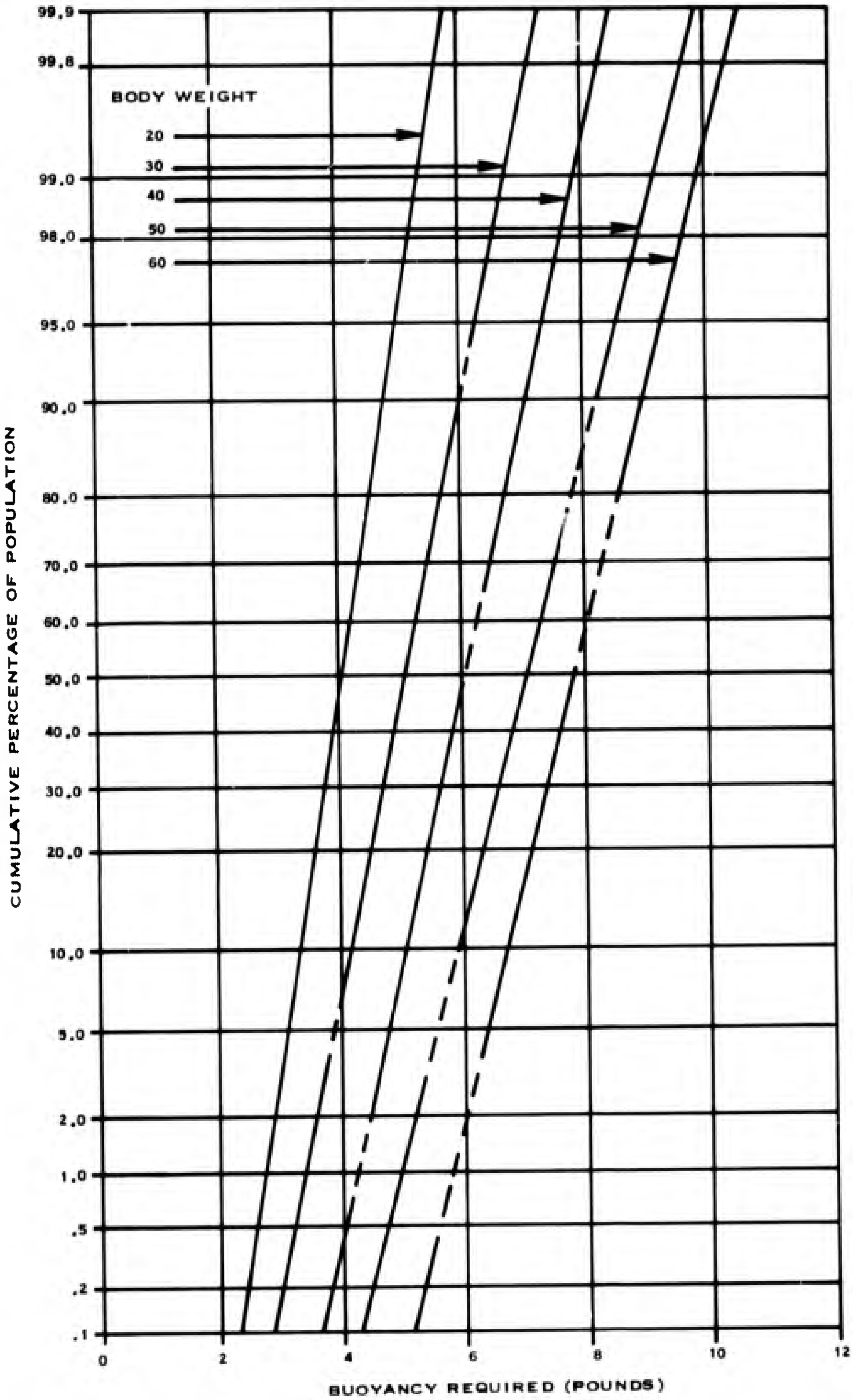


FIGURE II-5. Buoyancy Requirements for Children

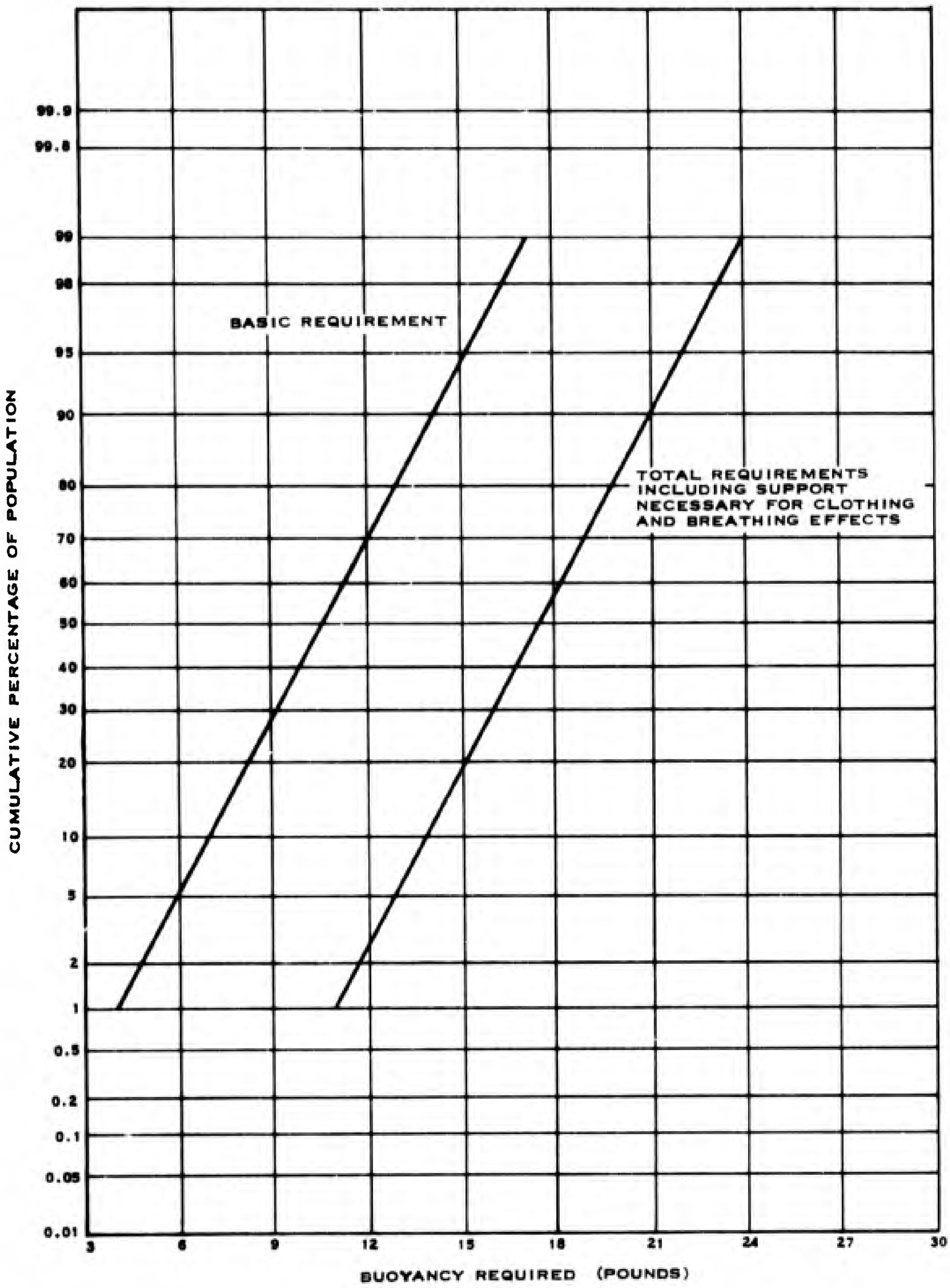


FIGURE II-6. Buoyancy Requirements for Adults

(1) General Requirement

A conscious person immersed in water will, unless the water is unusually warm, eventually weaken, lose consciousness, and die of failures of basic functions caused by a drop in body temperature. The time required to cause unconsciousness and death is primarily a function of the water temperature. Figure II-7 shows the times at which 50 percent of immersed persons would become extremely weakened or unconscious and also the time at which 50 percent of immersed persons would die of exposure. The difference between these two time values is effectively the difference in survival time between persons wearing a personnel flotation device with attitude-achieving capability and those wearing flotation devices without this capability. An analysis of these data was made to determine the increase in probability of survival as a function of time for different water temperature ranges when the personnel flotation device can maintain the body in a safe attitude. Results are shown in Figure II-8.

(2) Specific Attitude Requirements

The human body tends to float in a face-down position in the water. The reason for this tendency is the nature of the

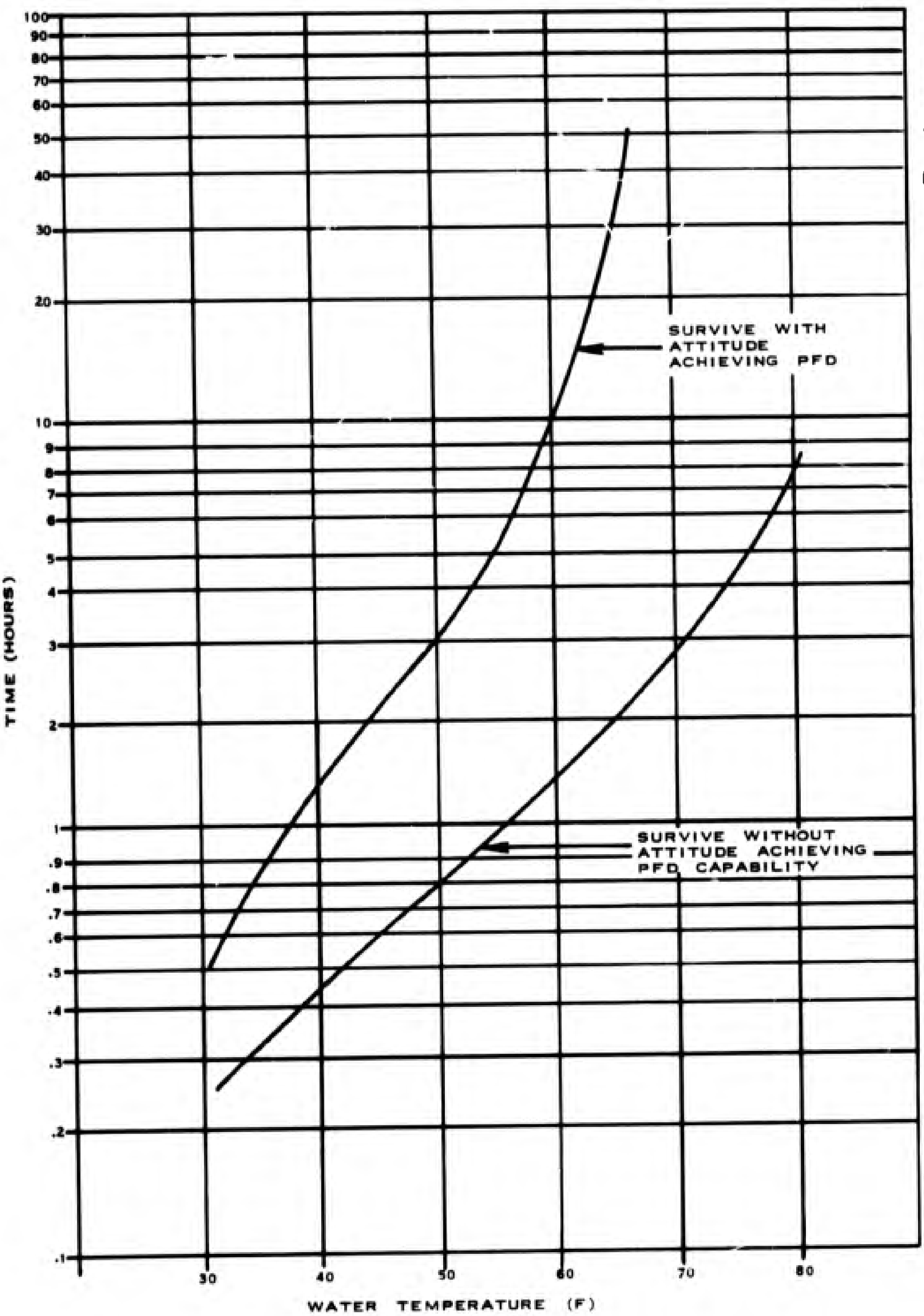


FIGURE II-7 Probability of Survival for People Using Personnel Flotation Devices Without Safe-Attitude-Achieving Capability

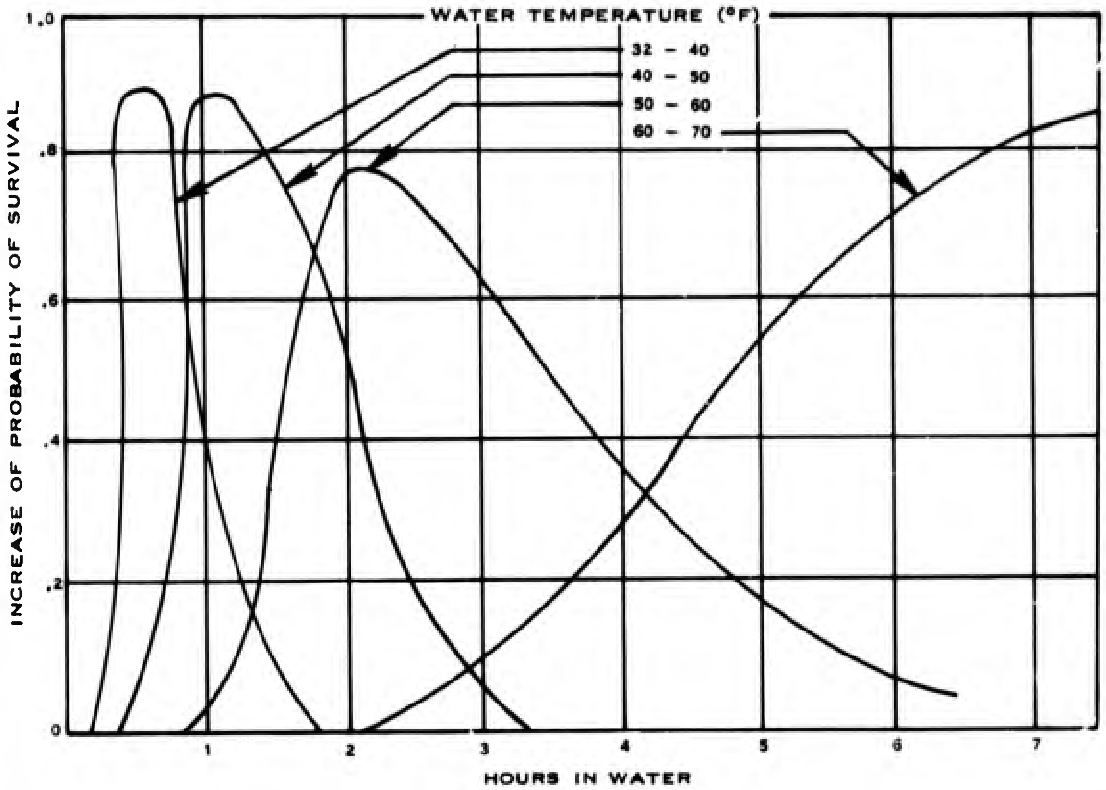


FIGURE II-8. Increase in Probability of Survival Due to PFD Capability to Orient Person in Safe Attitude

forces acting on the body in the water, with the head being the principal force. Figure II-9 shows models of the human body and the forces acting on it when it floats in the water.

Figure II-10 shows the torque required, in inch-pounds, to keep the body stabilized in any angle in the water. When α = -90 degrees, the body floats in a face-up position; when α = 0 degrees, the body is in a vertical position. The angles at which zero torque occurs should be the natural positions of the human body. It can be seen that, if the head is tilted backward while the body is also inclined backward, the body

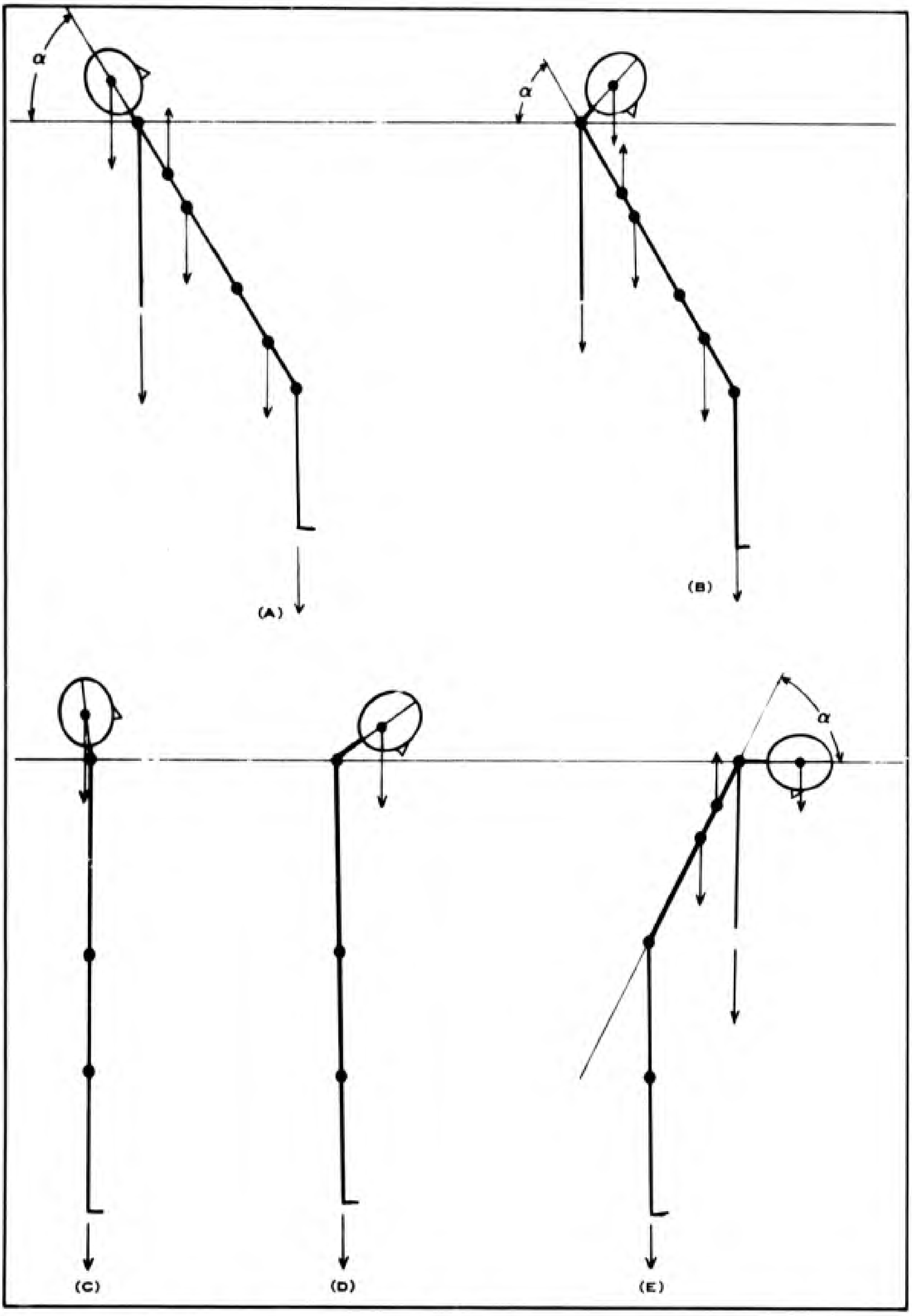


FIGURE II-9. Forces Acting on the Floating Man

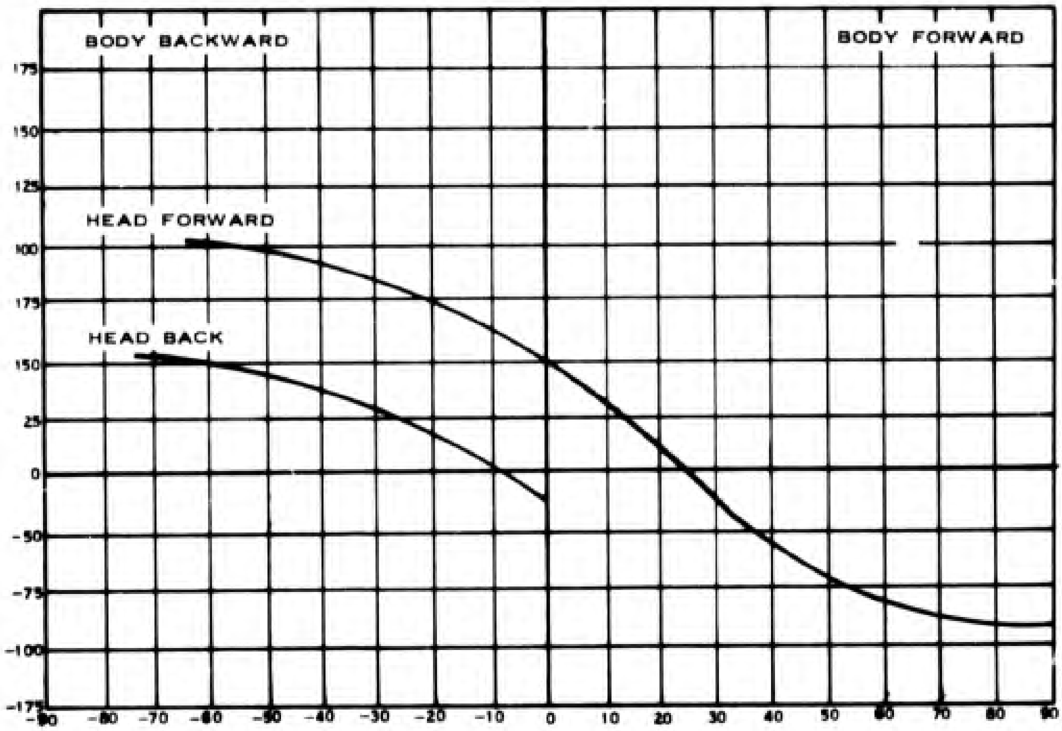


FIGURE II-10. Torque Required to Maintain a Body in Various Attitudes

will stabilize at about -5 degrees from vertical; but with very little additional torque (caused by wave action, clothing, etc.), the body would slip over toward a face-down attitude. The head should fall from a back-tilted angle to a forward-tilted one when the body attitude is about +5 to +10 degrees. This would result in torsion of the body farther forward until it floats in a stable, face-down position of about +30 degree attitude. Since the head can readily bend 65 degrees forward, the face would be immersed in the water at this stabilized attitude. The body must be inclined at an angle of approximately -60 degrees for a head tilted forward to be vertical. The body must be inclined at an angle of -30 to -40 degrees from vertical to keep the nose and mouth out of the water, when the head is tilted forward. Therefore, a personnel flotation device must provide sufficient torque to have the body stabilized at an attitude between 30 degrees and 60 degrees backward from the vertical.

(3) Turning Moment Requirements

It was not possible in this study to define the magnitude of the turning moment that a safe PFD should have. There were no data available to define the natural resistances of the body to turning nor the viscous shear forces involved. Without these data it was not possible to develop any creditable relationships among the induced turning moment, the magnitude of the turning moment, and the time to turn.

The turning moments were calculated to determine the zero turning moment angle (if any existed) and the stable angle(s) for each PFD configuration, and also to determine for the body in a forward prone position the relative magnitude of forces that would be acting on a body in a forward prone position to turn it face up or keep it face down. However, any analysis of the jackets with respect to time to turn must await water tests to provide data on the basic relationships previously mentioned.

5. SHAPE AND LOCATION OF BUOYANT MATERIAL

A study was made to determine the effects of the location, shape, thickness, and density of buoyant materials on the provided buoyancy and attitude-achieving capabilities of a jacket-type PFD. Ten configurations, representing three different thicknesses and two different material densities, were structured for the front buoyant section of a jacket-type personnel flotation device. Four configurations of materials, also representing three thicknesses and two material densities, were structured for the back buoyant section. Figure II-11 illustrates these front and back sections. The rationale used in defining these shapes was to have two lengths of material, eighteen and nine inches long, as well as to have, for the front material, shapes reflecting the effects of sculpturing the upper section to enhance ease of movement. Table II-1 summarizes the results of this analysis.

A review of the results shows that any 18-inch long front section would result in an extremely dangerous condition--i. e., one in which the body will, when inclined forward, be forced into a face-down position and be maintained in that position with considerable force. This because the location of the center of the buoyancy (through which the buoyant force acts) falls to a position that induces a clockwise moment (see Figure II-12). The results of an analysis for the length

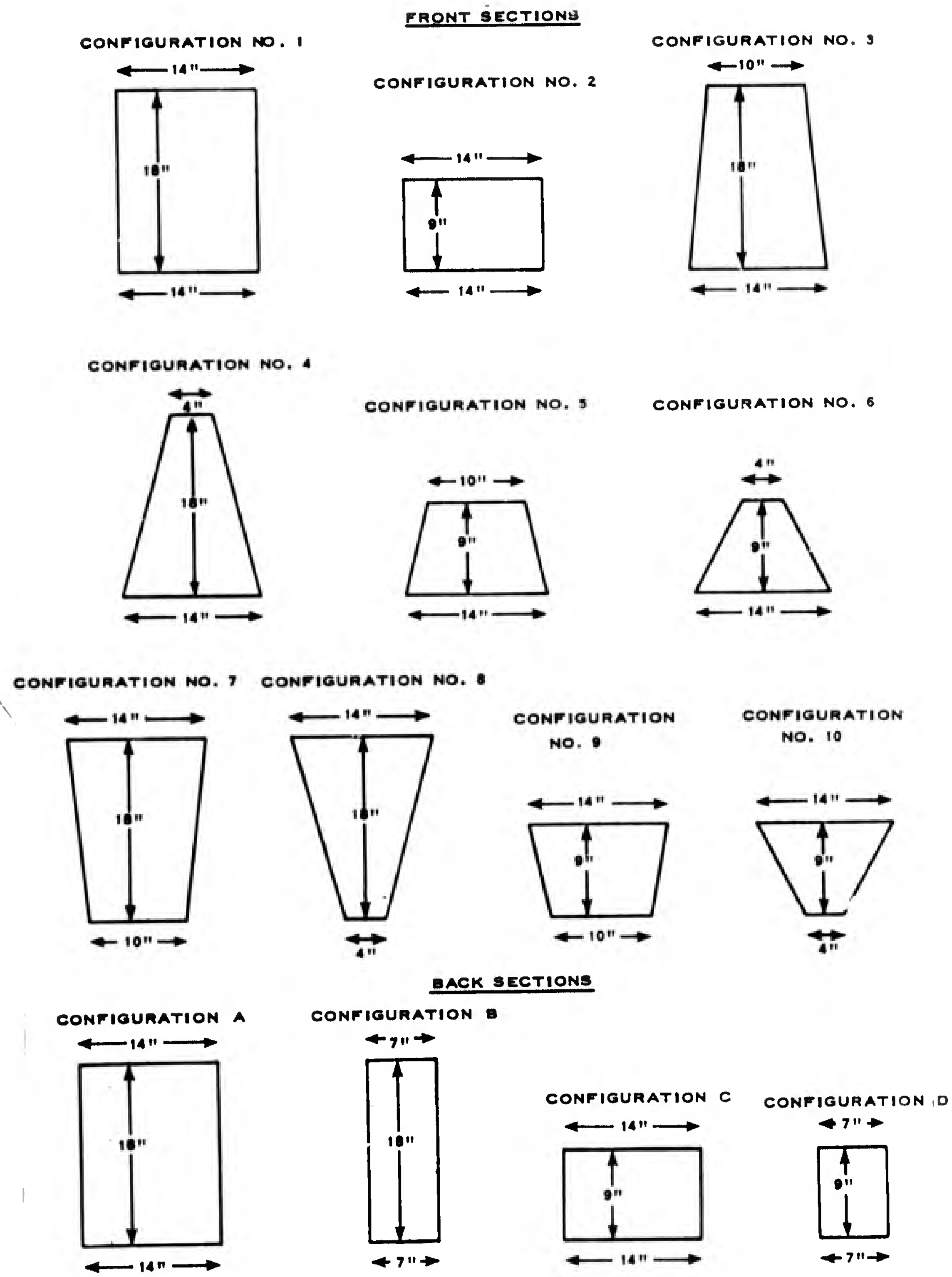


FIGURE II-11. Jacket-Type PFD Configurations

TABLE II-1. Stable Body Angle Person Will Achieve in Water from Various Initial Conditions Front Section--No Straps

FRONT SECTION - NO STRAPS								
CONFIGURATION 1		INITIAL CONDITION						Comments
Thickness	Density	Upright		Forward		Backward		
(Inches)	(#/Ft^3)	Angle[1]	Turning[2] Moment	Angle[1]	Turning[2] Moment	Angle[1]	Turning[2] Moment	
1	0.03	20	0	60	0	20	0	Configuration 1 is not safe since a person swimming, or whose body is inclined forward, would have the jacket forcing him into a stable, face-down position
1	15.00	20	0	70	0	20	0	
3	0.03	Over 60	150 (CC)	38	0	Over 60	150 (CC)	
3	15.00	Over 60	100 (CC)	43	0	Over 60		
5	0.03	Over 60	320 (CC)	41	0	Over 60	180 (CC)	
5	15.00	Over 60	235 (CC)	43	0	Over 60		
CONFIGURATIC' 2								
1	0.03	26	0	25	0	25	0	Configuration 1 is not safe since a person swimming, or whose body is inclined forward, would have the jacket forcing him into a stable, face-down position.
1	15.00	24	0	24	0	24	0	
3	0.03	25°	0	25°	0	25°	0	
3	15.00	10	0	10	0	10	0	
5	0.03	45	0	90	10 (C)	45	0	
5	15.00	37	0	87	0	37	0	
CONFIGURATION 3								
1	0.03	28	0	90	70 (C)	28	0	Configuration 1 is not safe since a person swimming, or whose body is inclined forward, would have the jacket forcing him into a stable, face-down position
1	15.00	27	0	90	25 (C)	28	0	
3	0.03	Over 60	85 (CC)	90	280 (C)	Over 60	80 (CC)	
3	15.00	Over 60	47 (CC)	90	190 (C)	Over 60	47 (CC)	
5	0.03	Over 60	155 (CC)	90	+300 (C)	Over 60	155 (CC)	
5	15.00	Over 60	105 (CC)	90	+300 (C)	Over 60	105 (CC)	
CONFIGURATION 4								
1	0.03	30	0	90	40 (C)	30	0	This configuration would not be safe. The one-inch thick arrangement would place a person face down from any initial body attitude. The three and five inch arrangements would force the person's body into a face-down condition if the person were swimming or inclined forward
1	15.00	30	0	90	25 (C)	30	0	
3	0.03	Beyond 60°	45 (CC)	90	250 (C)	Beyond 60°	45 (CC)	
3	15.00	Beyond 60°	15 (CC)	90	175 (C)	Beyond 60°	15 (CC)	
5	0.03	Beyond 60°	220 (CC)	90	380 (C)	Beyond 60°	220 (CC)	
5	15.00	Beyond 60°	155 (CC)	90	290 (C)	Beyond 60°	155 (CC)	

CONFIGURATION 5								
1	0.03	26	0	26	0	26	0	Configuration 5 is only safe if the material is more than 3 and less than 5 inches thick. A 3 inch thick arrangement does not place the person far enough back (20). The five inch material arrangement has a possibility of keeping a person face down. The one inch thick arrangement would settle the person into a face down position from any initial attitude.
1	15.00	26	0	26	0	26	0	
3	0.03	20	0	20	0	20	0	
3	15.00	0	0	0	0	0	0	
5	0.03	45	0	90	5 (C)	45	0	
5	15.00	33	0	90	25 (C)	30	0	
CONFIGURATION 6								
1	0.03	27	0	27	0	27	0	Configuration 6 is similar to Configuration 5, except that a five inch configuration would be safe. Any material arrangement whose thickness was any appreciable amount less than 5 inches would not be safe.
1	15.00	27	0	27	0	27	0	
3	0.03	23	0	23	0	23	0	
3	15.00	19	0	19	0	19	0	
5	0.03	35	0	90	5 (C)	35	0	
5	15.00	24	0	24	0	24	0	
CONFIGURATION 7								
1	0.03	27	0	90	50 (C)	27	0	There is no material thickness arrangement which would be safe in this configuration. A 1 inch thickness would place a person face down from any initial attitude. Any thickness greater than this would force the person face down if he were swimming or inclined forward.
1	15.00	26	0	90	25 (C)	26	0	
3	0.03	Beyond 60°	65 (CC)	90	210 (C)	Beyond 60°	65 (CC)	
3	15.00	Beyond 60°	32 (CC)	90	145 (C)	Beyond 60°	32 (CC)	
5	0.03	Beyond 60°	180 (CC)	90	330 (C)	Beyond 60°	165 (CC)	
5	15.00	Beyond 60°	110 (CC)	90	270 (C)	Beyond 60°	110 (CC)	
CONFIGURATION 8								
1	0.03	25	0	25	0	25	0	None of the three thicknesses investigated would be safe for the same reasons as those given for Configuration 7.
1	15.00	27	0	27	0	27	0	
3	0.03	59	0	90	95 (C)	59	0	
3	15.00	50	0	90	50 (C)	50	0	
5	0.03 60°	Beyond	35 (CC)	90	165 (C) 60°	Beyond	35 (CC)	
5	15.00	Beyond 60°	5 (CC)	90	110 (C)	Beyond 60°	5 (C)	
CONFIGURATION 9								
1	0.03	25	0	25	0	25	0	None of the thicknesses would be safe. A one inch thickness would, from any initial attitude, place a person in a face down position. The 3 and 5 inch arrangements would probably keep a person face down if he were swimming.
1	15.00	75	0	25	0	25	0	
3	0.03	19	0	90	10 (C)	19	0	
3	15.00	2	0	90	5 (C)			
5	0.03	33	0	90	10 (C)	33	0	
5	15.00	25	0	90	5 (C)	25	0	

CONFIGURATION 10								
1	0.03	26	0	26	0	26	0	The only safe arrangement would be a five inch thick one. Any lesser amount would force a person into a face-down attitude
1	15.00	25	0	26	0	25	0	
3	0.03	20	0	20	0	4	0	
3	15.00	15	0	15	0			
5	0.03	20	0	20	0	20	0	
5	15.00	14	0	14	0	14	0	
BACK SECTION - NO STRAPS								
CONFIGURATION A								
3	0.03	75	0 75	0	75	0		This back configuration, either by itself or in combination with any front configuration, would force a body into a face-down position
3	15.00	74	0	74	0	74	0	
5	0.03	58	0	58	0	58	0	
5	15.00	58	0	59	0	58	0	
CONFIGURATION B								This back configuration, either by itself or on combination with any front configuration, would force a body into a face-down position
3	0.03	74	0	74	0	74	0	
3	15.00	71	0	71	0	71	0	
5	0.03	68	0	68	0	68	0	
5	15.00	68	0	68	0	68	0	
CONFIGURATION C								
3	0.03	61	0	61	0	61	0	This back configuration, either by itself or in combination with any front configuration, would force a body into a face-down position
3	15.00	58	0	58	0	58	0	
5	0.03	51	0	51	0	51	0	
5	15.00	51	0	51	0	51	0	
CONFIGURATION D								This back configuration, either by itself or in combination with any front configuration, would force a body into a face-down position
3	0.03	53	0	53	0	53	0	
3	15.00	50	0	50	0	50	0	
5	0.03	51	0	51	0	51	0	
5	15.00	49	0	49	0	49	0	

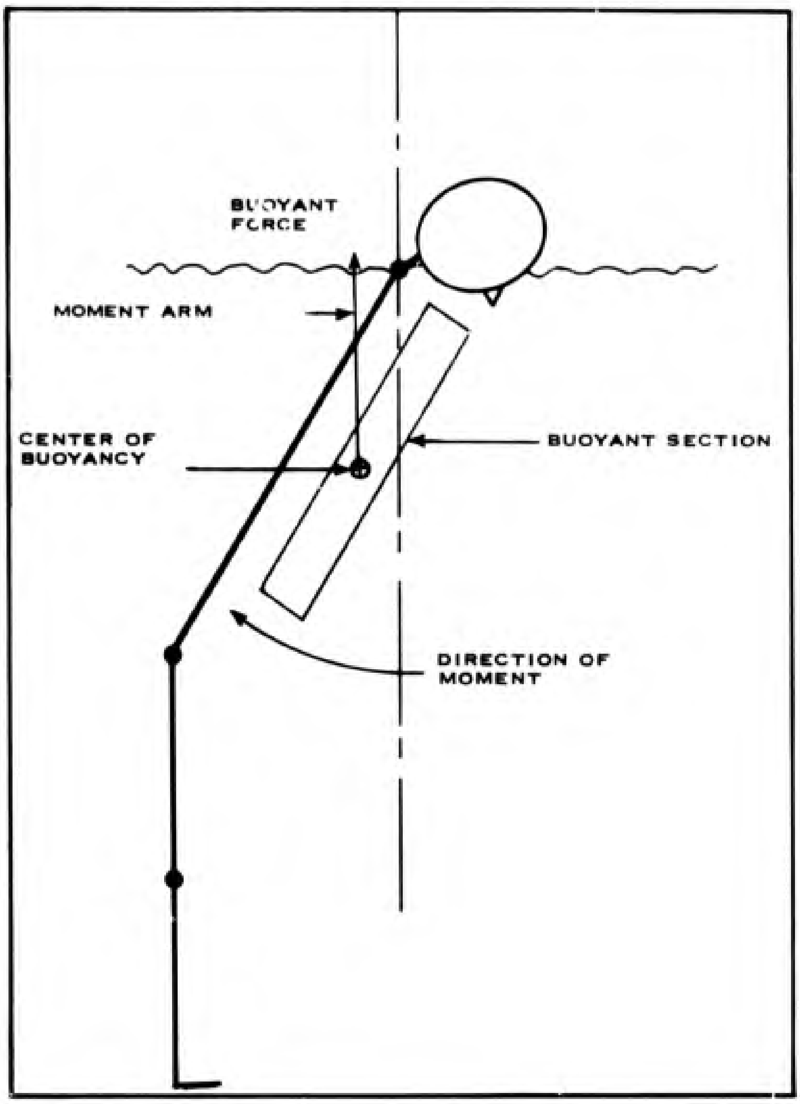


FIGURE II-12. Effects of Location of Buoyant Force Upon Induced Torque

of various configurations beyond which any material would induce an adverse moment is shown in Figure II-13. Sculpturing the material to provide greater arm movement dictates a reduction in the length and imposes a requirement for a thicker section to achieve sufficient buoyancy. Fortunately, increasing the thickness also permits an increase in the safe length.

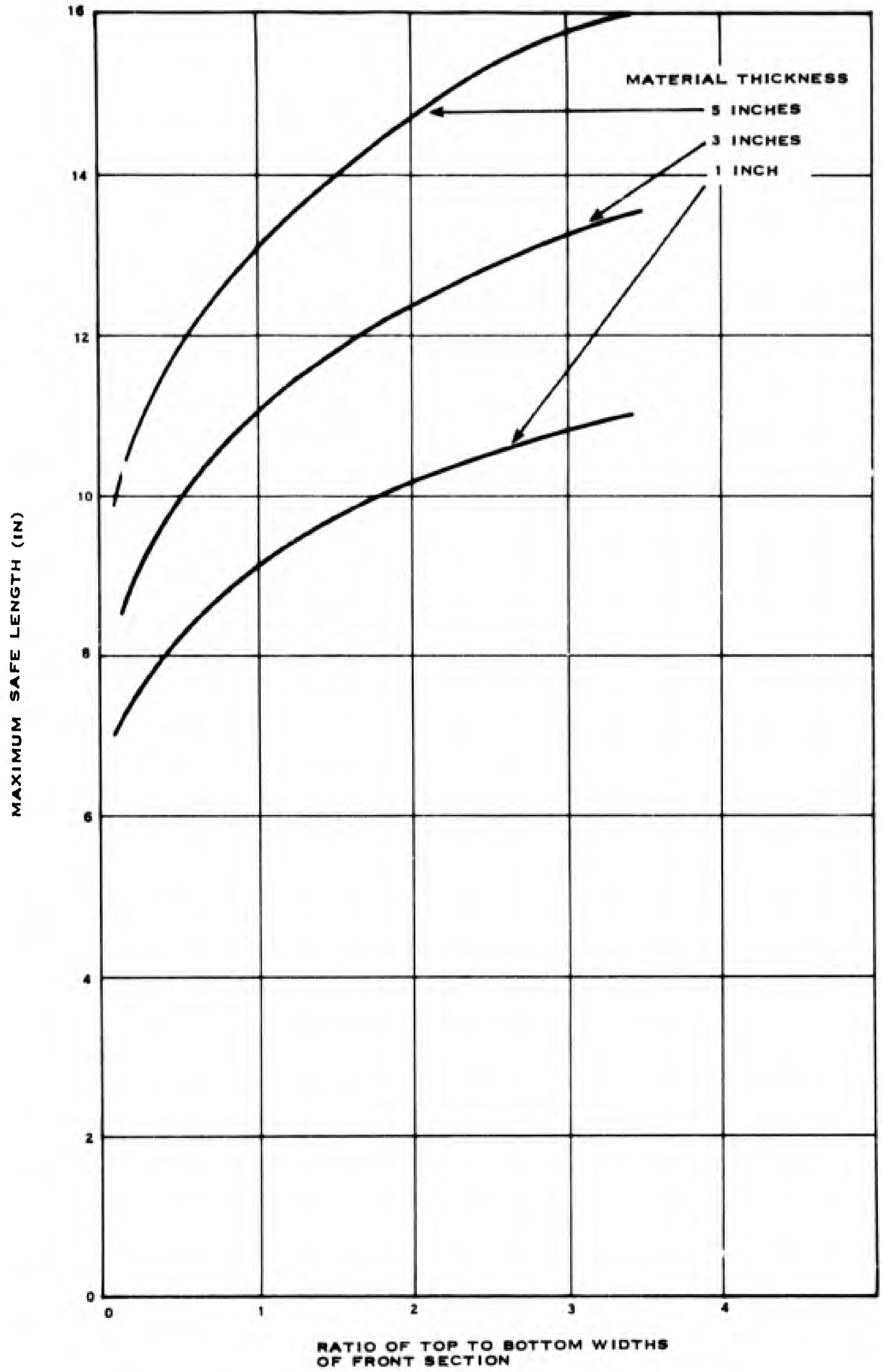


FIGURE II-13. Maximum Safe Lengths for PFD's as a Function of Sculpturing and Material Thickness (No Straps)

6. THICKNESS AND DENSITY OF MATERIAL

A PFD which always will turn a person on his back requires less material in the vest section than one which does not. The PFD with positive turning capability can have part of the buoyancy (about 7 pounds) in the collar section and the rest (15 pounds) in the vest section. A PFD without positive turning must have 22 pounds in the vest alone. Therefore, the safe device can have a thinner material thickness in the vest than any other type PFD. The density of the material is directly related to the thickness requirements of the material; the lighter the material, the lower the thickness required.

7. STRAP EFFECTS

An analysis was made of the effects of straps upon the forces acting to rotate the body. The purposes of straps on a jacket-type PFD should be to regulate the location of the buoyant force(s). The buoyant force(s) should act through the area of reaction, or where the buoyant material is strapped to the body. The previous analyses indicated that the force(s) should be located as high as possible on the chest of the immersed person to ensure a positive turning to a safe attitude. The effects of straps upon the capability of a configuration to achieve a safe attitude were analyzed. The first analysis examined the effects of using two straps, the higher one located a quarter of the distance from the top of the configuration and the second one located three

TABLE II-2 Material Thickness Requirements With and Without Straps

Configuration	1		2		3		4		5	
Material Density[1]	.03	15	.03	15	.03	15	.03	15	.03	15
Thickness to Achieve Buoyancy[2]	2.4	3.2	4.9	6.3	2.9	3.7	3.8	4.9	5.4	7.3
Thickness to Achieve Safe Attitude[3]-- No Straps	No Safe Condition		5+	5+	No Safe Condition		No Safe Condition		5+	5+
Thickness to Achieve Safe Attitude[3]	2.0	2.5	5+	5+	2.2	3.0	3.0	3.7	5+	5+

Configuration	6		7		8		9		10	
Material Density[1]	.03	15	.03	15	.03	15	.03	15	.03	15
Thickness to Achieve Buoyancy[2]	7.6	9.6	2.9	3.7	3.8	4.9	5.4	7.3	7.6	9.6
Thickness to Achieve Safe Attitude[3]-- No Straps	5+	5+	No Safe Condition		No Safe Condition		5+	5+	5+	5+
Thickness to Achieve Safe Attitude[3]	5+	5+	2.3	3.0	3.5	4.5	5+	5+	5+	5+

---

[1] lb/ft^3

[2] All buoyancy must be contained in vest section of PFD; 22 pounds of buoyancy was assumed required to keep a person in a vertical position in the water

[3] It was assumed that the buoyancy could be divided between the vest and collar; 7 pounds was assumed to be contained in the collar and 15 pounds in the vest. A safe body attitude was assumed to be at least 30 degrees inclined backward from vertical. Buoyancy as a function of thickness not calculated for thicknesses in excess of five inches.

quarters of the distance down. The results of this analysis were predictable; this arrangement produced no significant change from the no-strap condition. The second analysis examined a single-strap condition with the strap located at any of three locations, three, six, or nine inches from the top of the configuration. The results showed that a configuration, which without straps did not have the positive turning capability, could have this capability with properly placed straps. A summary of the analysis of effects of a single strap is shown in Table II-3.

8. THROW-TYPE PERSONNEL FLOTATION DEVICE REQUIREMENTS

An analysis was made to assess both the requirements and the effectiveness of throw-type personnel flotation devices. This analysis was limited to the accident condition in which a person falls overboard from a craft but one or more other persons remain on the craft to attempt to threw the accident victim a personnel flotation device. This type of accident constitutes about 25 percent of all water accidents. The analysis took into account differences in ship speeds, differences in the time required for the thrower to obtain access to the personnel flotation device, and differences in the distance and accuracy with which the devices could be thrown. One factor recognized to be of great importance--the effect of wind on throw distance and accuracy

TABLE II-3 Stable Body Angle Person Will Achieve in Water from Various Initial Conditions

Front Section--One Strap

FRONT SECTION - NO STRAPS									
CONFIGURATION		INITIAL CONDITION							Comments
Number	Material Thickness	Distance of Strap From Top	Backward		Upright		Forward		
			Stable Angle	Torque	Stable Angle	Torque	Stable Angle	Torque	
1	1	3	12	0	12	0	12	0	Configuration 1 will provide a capability to achieve a positive safe attitude when one strap is used and located three inches down from top for both a three and five inch thick material
		6	15	0	15	0	15	0	
		9	17	0	17	0	17	0	
	3	3	60	150 (CC)	60	150 (CC)	60	150 (CC)	
		6	60	150 (CC)	60	150 (CC)	90	10 (C)	
		9	60	150 (CC)	60	150 (CC)	90	75 (C)	
	5	3	60	320 (CC)	60	320 (CC)	60	320 (CC)	
		6	60	320 (CC)	60	320 (CC)	90	95 (C)	
		9	60	320 (CC)	60	320 (CC)	90	205 (C)	
2	1	3	18	0	18	0	18	0	Configuration 2 will provide a capability to achieve a positive safe attitude when a five inch thick configuration is used and a single strap located no more than seven inches down from the top
		6	21	0	21	0	21	0	
		9	22	0	22	0	22	0	
	3	3	25	0	0	0	0	0	
		6	25	0	0	0	0	0	
		9	25	0	0	0	0	0	
	5	3	45	0	45	0	45	0	
		6	45	0	45	0	45	0	
		9	45	0	45	0	90	45 (C)	
3	1	3	13	0	13	0	13	0	Configuration 3 will provide a capability to achieve a positive safe attitude for both a three and five inch thick arrangement. A single strap located no more than six inches down is required for the three inch thick arrangement. A single strap located no more than 3.5 inches down is required for the five inch thick arrangement
		6	16	0	16	0	16	0	
		9	18	0	18	0	18	0	
	3	3	60	85 (CC)	60	85 (CC)	60	85 (CC)	
		6	60	85 (CC)	60	85 (CC)	60	85 (CC)	
		9	60	85 (CC)	60	85 (CC)	90	45 (C)	
	5	3	60	155 (CC)	60	155 (CC)	60	155 (CC)	
		6	60	155 (CC)	60	155 (CC)	90	85 (C)	
		9	60	155 (CC)	60	155 (CC)	90	155 (CC)	

TABLE II-3. (Continued)

4	1	3	17	0	17	0	17	0	Configuration 4 will provide a capability to achieve a positive safe attitude for both the three and five inch thick arrangement. A single strap located no more than 8 inches down is required for the three inch thick arrangement. A single strap located no more than 5 inches down is required by the five inch thick arrangement.
		6	18	0	18	0	18	0	
		9	20	0	20	0	20	0	
	3	3	60	45 (CC)	60	45 (CC)	60	45 (CC)	
		6	60	45 (CC)	60	45 (CC)	60	45 (CC)	
		9	60	45 (CC)	60	45 (CC)	90	5 (C)	
	5	3	60	220 (CC)	60	220 (CC)	60	220 (CC)	
		6	60	220 (CC)	60	220 (CC)	90	20 (C)	
		9	60	220 (CC)	60	220 (CC)	90	90 (C)	
5	1	3	19	0	19	0	19	0	Configuration 5 will provide a capability to achieve a positive safe attitude if a single strap is located no more than 7.5 inches down from the top for a five inch thick arrangement.
		6	20	0	20	0	20	0	
		9	21	0	21	0	21	0	
	3	3	20	0	3	0	3	0	
		6	20	0	4	0	4	0	
		9	20	0	6	0	6	0	
	5	3	43	0	45	0	45	0	
		6	45	0	45	0	45	0	
		9	45	0	45	0	90	20 (C)	
6	1	3	20	0	20	0	20	0	Configuration 6 has a marginal capability to achieve a positive safe attitude. A five inch thick arrangement with a single strap located no more than 9 inches down from the top induces a stable body attitude at 350 backward, which is slightly less than required.
		6	21	0	21	0	21	0	
		9	22	0	22	0	22	0	
	3	3	10	0	10	0	10	0	
		6	11	0	11	0	11	0	
		9	14	0	14	0	14	0	
	5	3	35	0	35	0	35	0	
		6	35	0	35	0	35	0	
		9	35	0	35	0	35	0	
7	1	3	13	0	13	0	13	0	Configuration 7 will provide a capability to achieve a positive safe attitude for both the three and five inch thick arrangement when a single strap is used. The strap should not be located more than six inches down for the three inch thick arrangement and no more than four inches down for the five inch thick arrangement.
		6	15	0	15	0	15	0	
		9	17	0	17	0	17	0	
	3	3	60	65 (CC)	60	65 (CC)	60	65 (CC)	
		6	60	65 (CC)	60	65 (CC)	60	65 (CC)	
		9	60	65 (CC)	60	65 (CC)	90	45 (C)	
	5	3	60	165 (CC)	60	165 (CC)	60	165 (CC)	
		6	60	165 (CC)	60	165 (CC)	90	65 (CC)	
		9	60	165 (CC)	60	165 (CC)	90	165 (C)	

TABLE II-3. (Continued)

8	1	3 6 9	17 19 20	0 0 0	17 19 20	0 0 0	17 19 20	0 0 0	Configuration 8 will provide a capability to achieve a positive safe attitude when one strap used for both the three and five inch thick arrangements the strap should be no more than 8 inches down for the three inch and five inches down
	3	3 6 9	58 58 58	0 0 0	58 58 58	0 0 0	58 58 90	0 0 5 (C)	
	5	3 6 9	60 60 60	35 (CC) 35 (CC) 35 (CC)	60 60 60	35 (CC) 35 (CC) 35 (CC)	60 90 90	35 (CC) 20 (C) 90 (C)	
9	1	3 6 9	19 20 21	0 0 0	19 20 21	0 0 0	19 20 21	0 0 0	The comments on configuration 9 are the same as those for configuration 6 except that the strap should not be located more than seven inches down for the five inch thick arrangement
	3	3 6 9	13 13 13	0 0 0	13 13 13	0 0 0	13 13 13	0 0 0	
	5	3 6 9	35 35 35	0 0 0	35 35 35	0 0 0	35 35 90	0 0 20 (C)	
10	1	3 6 9	20 20 21	0 0 0	20 20 21	0 0 0	20 20 21	0 0 0	Configuration 10 will not provide a capability to achieve a positive safe attitude using a single strap
	3	3 6 9	11 12 14	0 0 0	11 12 14	0 0 0	11 12 14	0 0 0	
	5	3 6 9	20 20 20	0 0 0	20 20 20	0 0 0	20 20 20	0 0 0	

1 Material Density 0.03 lbs ft^3

2 Distance is measured from top of configuration (inches)

and on the probability of the device being driven along the surface of the water--was not considered in the analysis because of the lack of data. A device such as a buoyant cushion, with a very low draft and high freeboard, could be driven at a rate of approximately three times the swimming speed of the average man. Therefore, the conclusions drawn indicate an effectiveness that is probably better than the actual conditions warrant.

The probability of survival is equal to the person's ability to swim the distance to the thrown personnel flotation device. This distance is a function of the distance and the accuracy with which it can be thrown to the immersed person. The results of this analysis indicate that, as the ship's speed increases, the minimum time of access to a device falls sharply. This condition is accentuated as the distance and accuracy with which the devices can be thrown is reduced. Figure II-14 was developed to indicate the effect of throw distance on the effectiveness of a throw-type PFD. It shows the relationships between ship speed throw accuracy, time to obtain access to the PFD, and probability of survival for a device that can be thrown 50 feet and another than can be thrown 150 feet. (This larger distance represents a limiting case, because there is small likelihood that any PFD could be thrown 150 feet from an unstable platform such as a pleasure craft.)

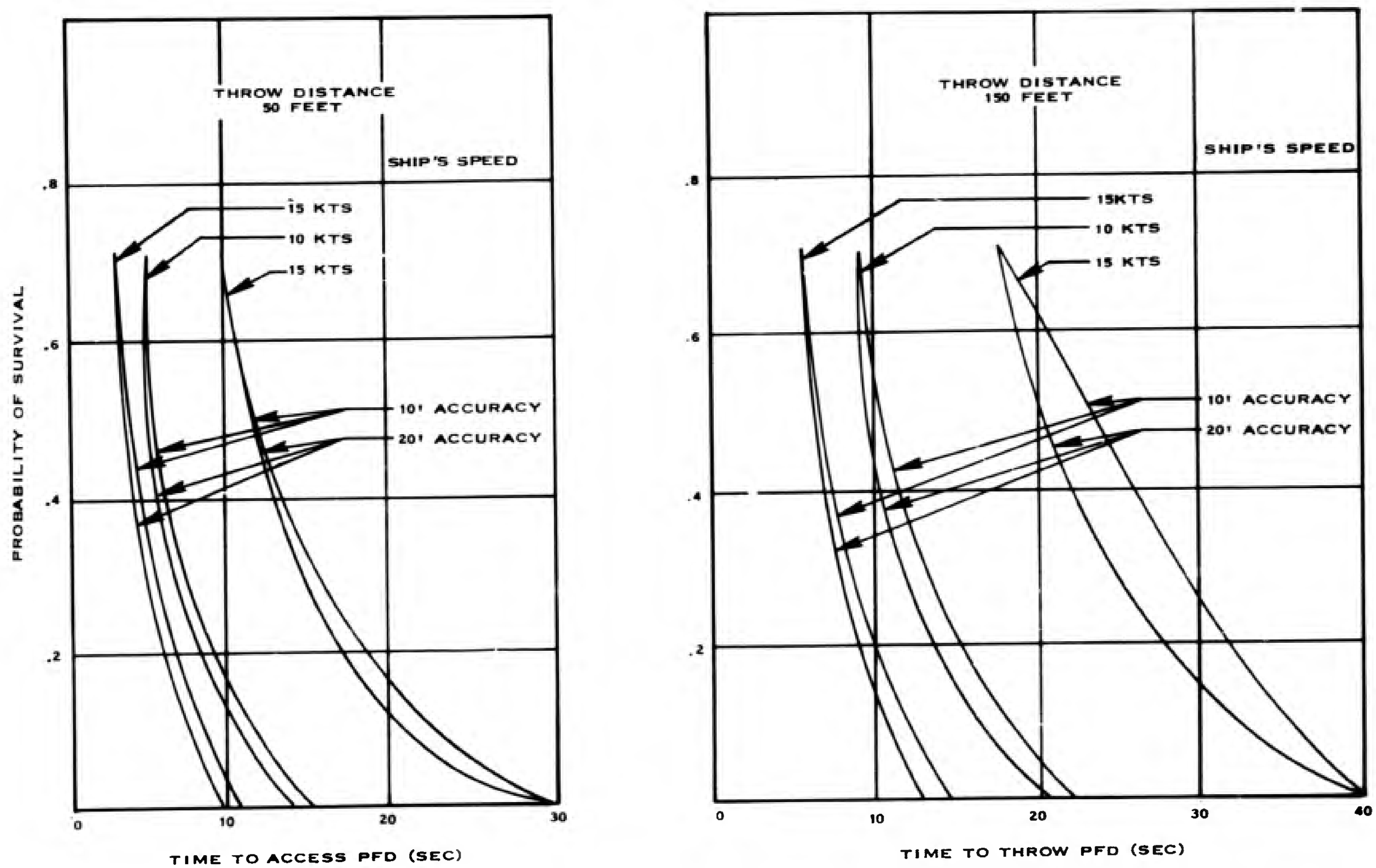


FIGURE II-14. Estimated Probability of Survival for Throw-Type Personnel Flotation Devices

The effects of throwing accuracy are reflected by the upper and lower limits for each family of curves. The results indicate that a device which can only be thrown 50 feet must be thrown within about five seconds after a person enters the water, if the immersed person is to have any reasonable chance of reaching the device. This result is for a craft traveling no faster than ten knots. A device which can be thrown 150 feet must be thrown within approximately ten seconds to achieve the same effect under the same conditions. It is apparent that any type devices which are to be thrown to aid an immersed person must be readily available, and, even under these conditions, it is questionable that the device will be of much value in saving the person's life. It is estimated that approximately 20 percent of the people could not swim more than a few feet, and a device of this type is of no use unless reached by the swimmer.

9. CONCLUSIONS

The following conc' :ions are based upon the preceding analyses.

(1) Buoyancy Requirements

The buoyancy requirements of children appear to have a strong correlation with their weight. A buoyancy of 7. 3 pounds will support 95 percent of the children weighing 40 pounds; however, 7.3 pounds will only support 65 percent of the children weighing 50 pounds, and only 29 percent of the children weighing 60 pounds. The expression, $B = 4.4 + 0.08W$, where B is the buoyancy required in pounds and W is the child's weight in pounds, describes the weight/buoyancy requirement for children. Children's jacket-type personnel flotation devices should be classed by body weight. If only two sizes are to be used, children weighing between 60 and 90 pounds should require 12 pounds of buoyancy; children weighing 60 pounds or less should be provided with 9 pounds of buoyancy.

The buoyancy requirements of adults do not appear to have significant correlation with body weight. Twenty-two pounds of buoyancy appear to be necessary to support 95 percent of adults in still water. The effects of waves upon buoyancy requirements were not established in this study, and, therefore, these requirements may have to be adjusted to account for wave action.

(2) Body Attitude Requirements

The immersed person should be maintained at any angle of 30 to 60 degrees from vertical, inclined toward the back. The 30-degree angle is a minimum safe value necessary to keep an unconscious person's face out of the water when the head is bent forward.

Three principal conditions can be induced by a PFD. The first condition is one in which the body will stabilize in a safe angle of 30 to 60 degrees backward in the water from any initial body attitude. A PFD with this capability is defined in this study as a safe PFD with positive turning capability. In the second condition, the body will stabilize in a safe angle if the person is initially in a vertical or body-back angle. A PFD with this capability is defined as an adequate PFD. The third condition is one in which a PFD will induce a person to be turned face down, or, if in a body-forward condition, will induce a significant turning moment keeping him in that position. A PFD with this characteristic is defined as an unsafe PFD.

(3) Jacket-Type Personnel Flotation Device Requirements

The following sections discuss various requirements for jacket-type personnel flotation devices. These requirements are based on the assumption that the PFD should, to be a positively safe device, be capable of turning a person from any initial body attitude to a body position between 30 and 60 degrees backward from vertical.

1. Front Section

The front section of a jacket-type personnel flotation device is sensitive to a number of factors, when assessing its capability to right a person to a safe body attitude. Straps and strap location are extremely important. A single strap located as high as possible on the chest is best; multiple straps tend to defeat the advantage of straps with respect to a righting capability. A front section without straps cannot be too long; however, the maximum length is dependent upon its geometry, thickness, and density. A design which places as much material on the upper chest as possible is the preferable design.

2. Back Section

No buoyant material should be firmly attached to a person's back if a righting capability is desired. Buoyant material located on the back will keep a person face down in the water.

3. Collar Section

The collar section should provide sufficient buoyancy to support the head and should be free floating. Theoretically, no support is required if the body only goes back 60 degrees, since the head bends only a small angle backward; however, to keep the body from going much farther backward, and to support the head if the body does go farther back, about 7 pounds of buoyancy are required in the collar. This buoyancy can not be included as part of the total buoyancy requirement of the PFD unless the device always turns a person onto his back.

4. Turning Moment

It was not possible, without making an excessive number of unsupported assumptions, to determine the necessary magnitude of the turning moment or torque of a personnel flotation device. The critical relationship is between torque and time to achieve a safe attitude. This could not be estimated without testing, since no data currently exist on this relationship.

5. Throw-Type Devices

Throw-type devices, by their nature, are limited in value to the man-overboard type of accident. To have any significant value, they must be readily accessible and capable of being thrown a considerable distance.

III. TRADE-OFF AND EFFECTIVENESS STUDY

1. SUMMARY

The majority of passengers on pleasure craft do not wear personnel flotation devices. Eighty percent of the people found drowned were not wearing personnel flotation devices, despite their availability on the vessels from which these people entered the water (see Figure II-2). It is apparent from the preceding analyses that a safe device must have a considerable amount of material located as high as possible on the upper chest. However, devices of this type have been found to have very low wear acceptability by people. A personnel flotation device that is not worn can be assumed to be unavailable to a person accidentally entering the water.

There is a trade-off situation between wear acceptability and the overall safety of the personnel flotation device. A trade-off study was conducted to determine the relative merit of different configurations, the effects of material density, and material processing or design of the inherently inflatable materials. In addition, a personnel flotation device employing an inflatable cell was considered in the study.

A series of analyses was made in the trade-off study. The first analysis evaluated each configuration with respect to separate factors influencing wear acceptance of a personnel flotation device, and developed a wear acceptability value for each configuration. This analysis defined the relative availability of each configuration. A second analysis was made to determine a percentage of the total population which would obtain sufficient buoyancy from the personnel flotation device configuration. The product of the configuration's availability (wear acceptance), and the percentage of the population supported by that configuration, provided an estimate of the short-term probability of survival for each configuration. A final analysis was made of the effectiveness of the different configurations, in which the effects of exposure were considered. The effects of exposure upon the probability of survival were calculated for each configuration, providing a total probability of survival estimate and an estimate of effectiveness.

The results of these analyses are summarized below.

(1) Significance of Inherently Buoyant Material and Its Design Application

An analysis of the significance of inherently buoyant material and its design application was made with reference to the accident condition in which a person is fully conscious at the time of his accidental entry into the water and is in danger of becoming unconscious only as the result of prolonged exposure to the water. Thus, the possibility that the wearer of the PFD might be injured or become unconscious before entering the water was specifically excluded. It should be noted that this study was a statistical analysis of mass data and did not take into account every possible individual event.

The purpose of the study was to investigate the trade-off relationships between wear acceptance of a configuration and such factors as material thickness, density, and design. Material thickness and density are extremely important with respect to the short-term probability-of-survival ratings, but wear acceptance, which determines whether or not persons in pleasure craft will wear the jacket-type PFD, has an important bearing on its actual effectiveness.

The most significant factor affecting the wear acceptance of a personnel flotation device is the thickness of the material. (The density of the material, while also a comfort factor, did not appear to be as important a factor in influencing willingness to wear.) The second most important factor was quality of design; i.e., sculpturing, venting, and articulation of the buoyant material.

PFD configurations that have the capability of maintaining their wearer in a safe attitude in the water are usually made of thicker and denser materials than those that lack this capability, and consequently they have less wear acceptance. The study results indicate that a PFD configuration that will place the wearer in a safe attitude is superior to one that does not, under conditions where the accidentally immersed person may be subjected to exposure in chilled water long enough to cause unconsciousness. In all other cases, the PFD that provides only buoyancy, because of its greater wear acceptance, is superior.

(2) Overall Evaluation

The total probability-of-survival values for all personnel flotation devices using inherently buoyant material ranged from poor to extremely poor. These results were obtained because of the difficulty in configuring a personnel flotation device which would have sufficient wear acceptance and still provide adequate buoyancy for the bulk of the adult population. The postulated inflatable flotation device had a significantly better estimated total probability of survival than any of the other configurations. This was due to the fact that a wear-acceptable configuration could be devised which could support 95 percent of the adult population in a safe attitude.

A reliability of 0. 90 was used in this assessment, since it was recognized that human error--for instance, failure to replace spent gas cartridges--could cause failure of the inflatable PFD, perhaps as often as once in ten usages. However, this is believed to be a conservatively high estimate of the incidence of failures of such devices attributable to human error.

2. WEAR ACCEPTANCE

Discussions were held with manufacturers and distributors and with persons who engage in pleasure boating to develop estimates of the factors that influence the willingness of boaters to wear a jacket-type PFD. The consensus was that, in general, people object to these devices because, in summer when most pleasure boating takes place, the jackets are hot and uncomfortable, impede their freedom of movement, and are unattractive. Several of the manufacturers and distributors reported that any device over one inch thick would be poorly received by the boating people, and that some boaters would not wear jackets regardless of their materials and design. The following observations were drawn as a result of these discussions.

(1) Weight

Weight, which is a product of material thickness and density, is a determining factor in wear acceptance. The heavier the PFD jacket, the less acceptable it will be. No estimates could be developed on the full relationship between weight and acceptance; a fairly rapid exponential drop-off in acceptance as a function of weight was postulated (see Figure III-1).

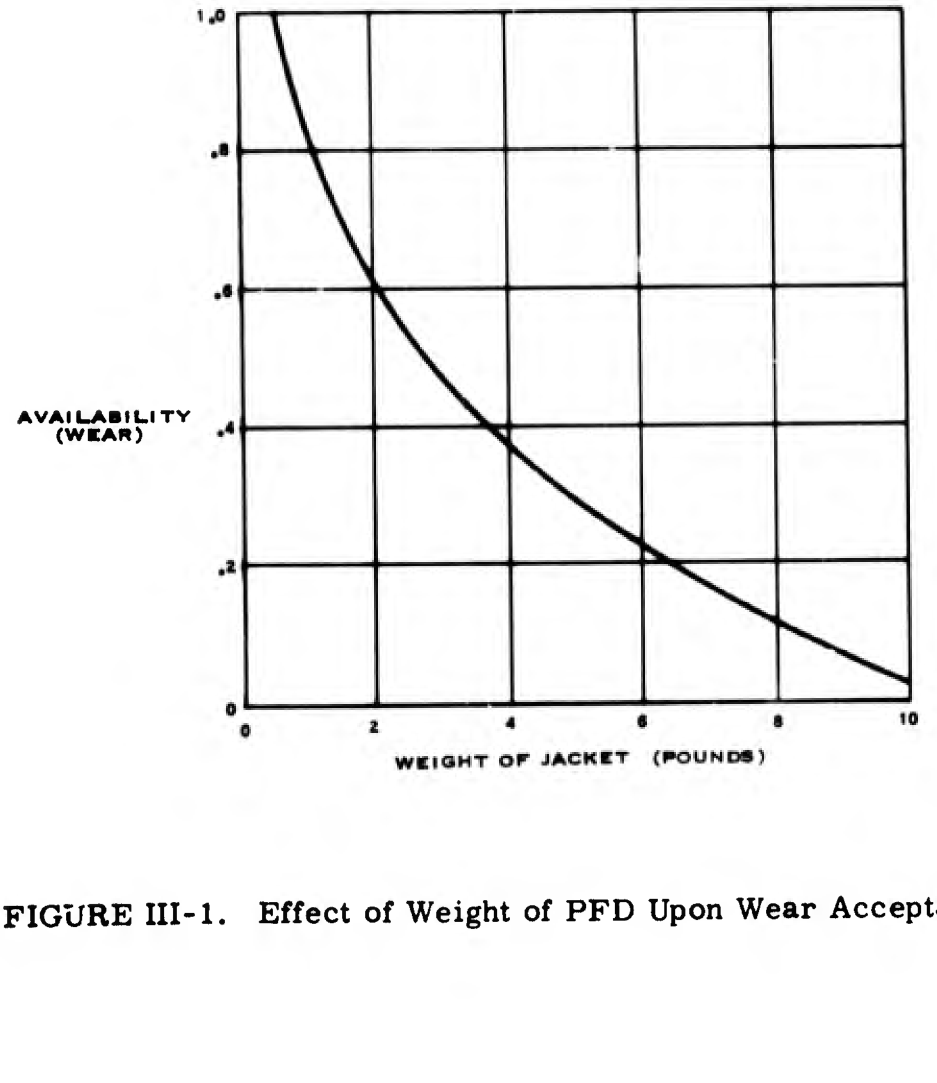


FIGURE III-1. Effect of Weight of PFD Upon Wear Acceptance

(2) Transpiration

Most recreational boating occurs in the warmer periods of the year. The jacket-type personnel flotation device restricts the flow of air and perspiration, and thereby increases the feeling of temperature discomfort. A device which covers most of the upper torso would have a very low wear acceptance because of its effect upon transpiration. However, if the same device were vented to permit a better flow of air, it would be more acceptable. Some people are out in boats to get a sun tan and that alone precludes wearing a device. No matter how ventilated it is, not all will wear it. Again, no data exist on the realtionship between transpiration and acceptance; Figure III-2 is the estimated relationship between these two factors.

(3) Ease of Movement

A jacket-type personnel flotation device can interfere with motion by restricting movement of arm and torso. Arm-motion restriction can be related to the amount of sculpturing of the buoyant material at the upper chest and the degree to which the buoyant material can be articulated. The restriction on torso bending can be related to the length of the front buoyant

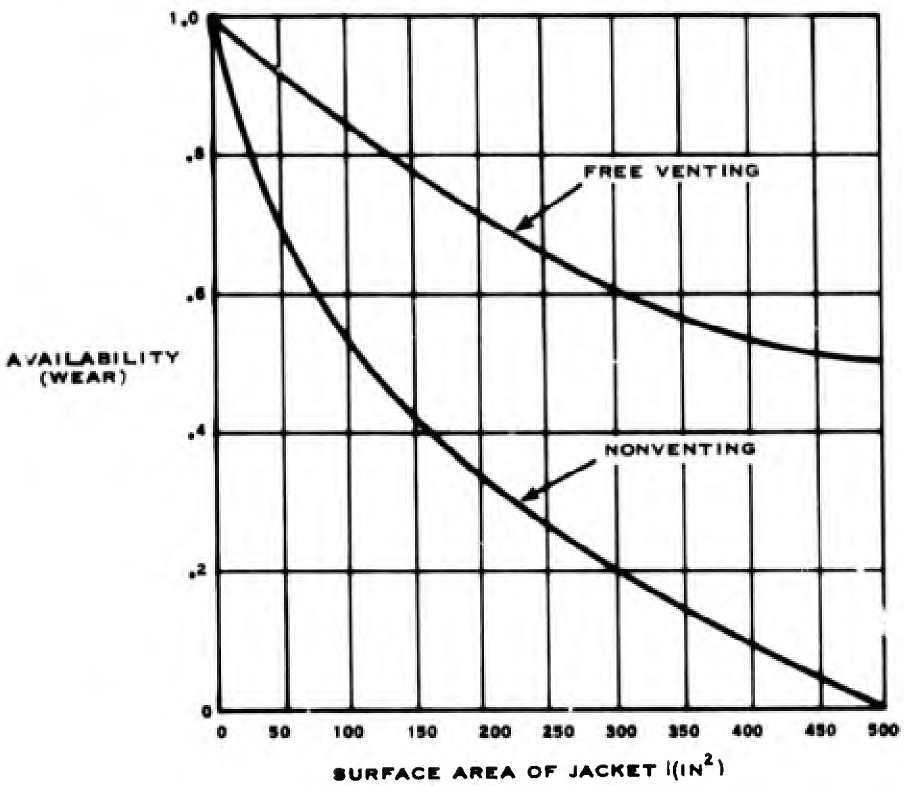


FIGURE III-2. Effects of PFD Transpiration Upon Wear Acceptance

section, and to the degree to which the section can be articulated. Figures III-3 and III-4 show the assumed relationships among material width at the shoulder, material length, thickness, articulation, and ease of movement for wear acceptance.

(4) <u>Aesthetics</u>

Aesthetics, as a factor, included all aspects of a jacket-type configuration which would cause a person to be more or less likely to wear a jacket due to appearance or social acceptability.

The jacket can be covered with various fabrics and designs to make it more attractive; however, the inherently buoyant material and its configuration and thickness will affect the appearance of the person wearing the jacket, no matter what is done to the jacket covering. People, especially young adults, will not accept a jacket which makes them appear unsightly. The significance of this in the rating of a jacket configuration can be expressed primarily in the jacket material's thickness. It has been assumed

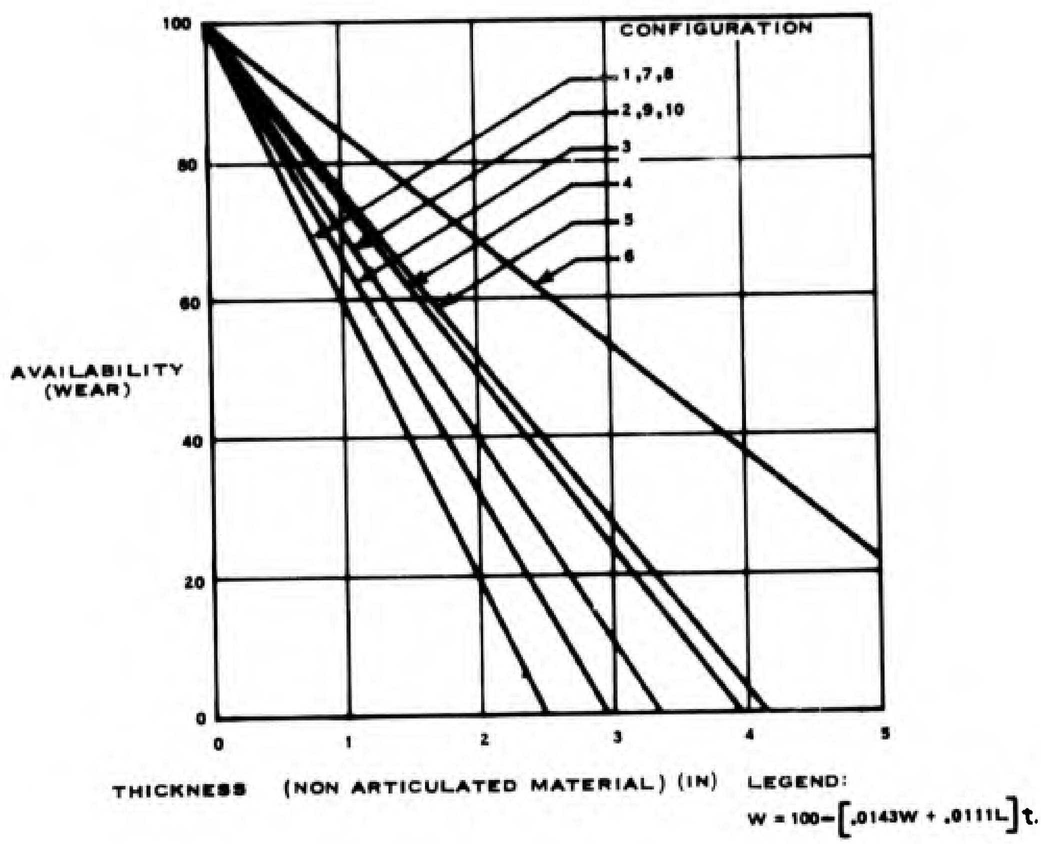


FIGURE III-3. Effects of Material Articulation Upon Wear Acceptance

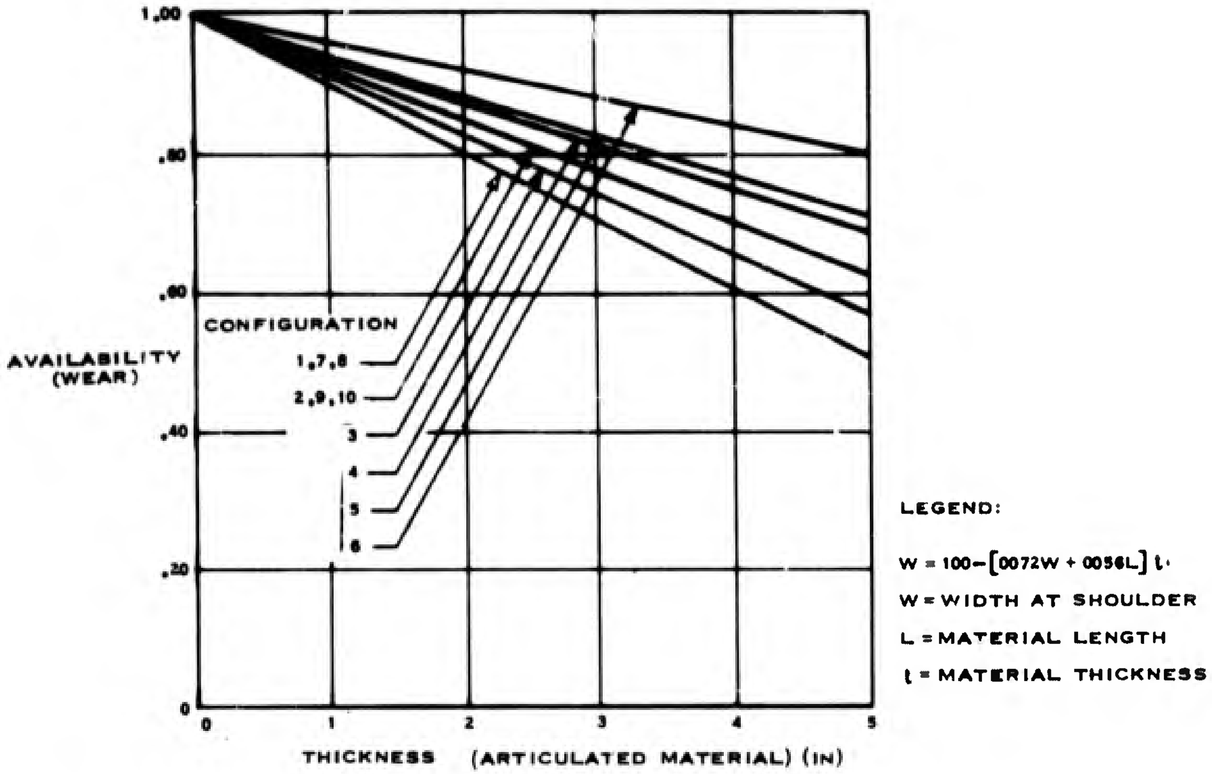


FIGURE III-4. Effects of Material Shoulder Width and Length Upon Wear Acceptance

that a jacket whose material is very thin will not be completely accepted because of the desire of many people not to wear any jacket, and the relatively limited social acceptance of personnel flotation devices, per se. Figure III-5 shows the relationship personnel flotation device thickness and its assumed values of wear acceptance based upon aesthetic factors.

(5) Combined Wear Acceptance

The four previously described factors were combined into a single wear-acceptance value. After considerable discussion,

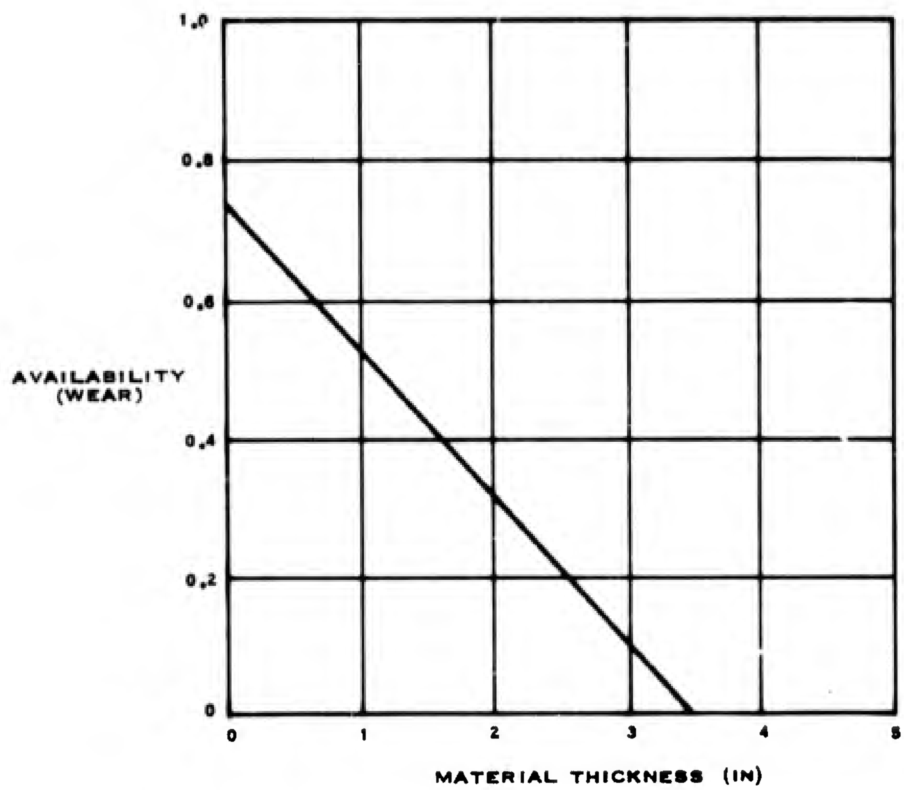


FIGURE III-5 Effects of Appearance Upon Wear Acceptance

it was concluded that aesthetics was the most important factor; if all other conditions were acceptable but it did make the person wearing it look unattractive, in his evaluation or the judgment of others, then there would be little likelihood of its being worn. The other three factors were judged to be of about equal importance to the pleasure-boating population. On this basis, the combined wear acceptance value (W_a) was made equal to $A(W + E_M + T)$, where (A) is the aesthetics value, (E_M) is the ease-of-movement value, and (T) is the transpirational value. The combined wear-acceptance values, as a function of material thickness, for each configuration, are shown in Table III-1. An eleventh configuration which was postulated was an inflatable jacket. The unfilled cell(s) were assumed to extend six inches down from the shoulder, to be fourteen inches wide, to have a thickness of about one-quarter inch, and to weigh about one pound. Two reliability values were assumed for the inflatable PFD. The higher value, 0.90, was believed to be a conservative estimate of its true capability to provide sufficient buoyancy to support 99 percent of the adult population. Its wear acceptance, on this basis, would be 0.54, and its availability would be 0.485.

3. SHORT-TERM PROBABILITY OF SURVIVAL

A short-term probability of survival was developed to show the effectiveness of the various configurations, when the effects of exposure to water were excluded. This probability of survival is the probability of a device being available when needed, and having sufficient buoyancy to keep the person's head out of water. It was assumed, in this analysis, that if a person was not wearing a jacket-type personnel flotation device, it would not be available to him if he had to enter the water accidentally. This assumption is not completely correct, since accidents can occur in which a person does have time to access and don a jacket. However, a majority of water fatalities appear to involve persons falling overboard or a boat capsizing. In these cases, it would seem that, unless the

TABLE III-1 Combined Wear Acceptance Value

CONFIGURATION		CONFIGURATION CHARACTERISTICS							
		MATERIAL DENSITY							
		15 LB FT³				0.03 LB FT³			
		ARTICULATION				ARTICULATION			
		NONE		HIGHLY		NONE		HIGHLY	
NO.	THICKNESS	NOT VENTED	VENTED	NOT VENTED	VENTED	NOT VENTED	VENTED	NOT VENTED	VENTED
1 (14X18X14)	1	.24	.32	.31	.38	.38	.47	.45	.53
	3	.01	.04	.03	.05	.04	.05	.06	.07
	5	.00	.00	.00	.00	.00	.00	.00	.00
2 (14X9X14)	1	.33	.39	.37	.43	.45	.53	.50	.57
	3	.03	.04	.05	.07	.05	.06	.07	.08
	5	.00	.00	.00	.00	.00	.00	.00	.00
3 (10X18X14)	1	.27	.34	.32	.39	.41	.49	.46	.54
	3	.02	.03	.04	.06	.04	.05	.06	.08
	5	.00	.00	.00	.00	.00	.00	.00	.00
4 (4X18X14)	1	.31	.38	.35	.41	.44	.52	.49	.56
	3	.03	.04	.05	.06	.05	.06	.07	.08
	5	.00	.00	.00	.00	.00	.00	.00	.00
5 (10X9X14)	1	.34	.40	.38	.44	.46	.53	.51	.58
	3	.03	.04	.06	.07	.04	.06	.07	.08
	5	.00	.00	.00	.00	.00	.00	.00	.00
6 (4X9X14)	1	.39	.45	.41	.47	.51	.57	.54	.60
	3	.05	.06	.07	.08	.07	.08	.08	.09
	5	.00	.00	.00	.00	.00	.00	.00	.00
7 (14X18X10)	1	.26	.33	.31	.38	.39	.47	.46	.54
	3	.02	.03	.04	.05	.04	.05	.06	.07
	5	.00	.00	.00	.00	.00	.00	.00	.00
8 (14X18X4)	1	.29	.35	.34	.41	.41	.49	.48	.56
	3	.02	.04	.05	.06	.04	.05	.07	.08
	5	.00	.00	.00	.00	.00	.00	.00	.00
9 (14X9X10)	1	.34	.40	.39	.45	.47	.53	.51	.58
	3	.03	.05	.06	.07	.05	.06	.07	.08
	5	.00	.00	.00	.00	.00	.00	.00	.00
10 (14X9X4)	1	.37	.42	.41	.46	.48	.54	.52	.55
	3	.05	.05	.06	.07	.05	.06	.07	.09
	5	.00	.00	.00	.00	.00	.00	.00	.00
11 (14X8X14)	0.25	-	-	0.54[1]	-		-		

1 – MATERIAL DENSITY NOT APPROPRIATE

person is wearing the personnel flotation device, there is very little chance of his acquiring one after he enters the water.

It can be seen from Table III-1 that the thinner the material used in a personnel flotation device, the more likely it is to be worn or to be available. Similarly, the smaller the configuration, the more likely it is to be worn. Both features have a direct relationship to the total amount of buoyant material contained in the jacket; the less the buoyant material, the greater its likelinood of being worn. However, it is apparent that with less buoyant material, fewer people would be supported by the buoyancy provided. There should be an optimal condition which provides the greatest possible safety when both availability and buoyant support are considered. An analysis was made to determine the optimal condition and the maximum safety value. This analysis consisted of multiplying the combined wear-acceptance values times the device's reliability times the percentage of the adult population which would be supported by the provided buoyancy. The reliability for the inherently buoyant material was assumed equal to 1.00; the reliability of the inflatable device was assumed equal to 0.50 or 0.90. The results of this analysis for the ten front-section configurations are shown in Figures III-6 through III-15. The analysis considered the maximum and minimum densities, the articulated,

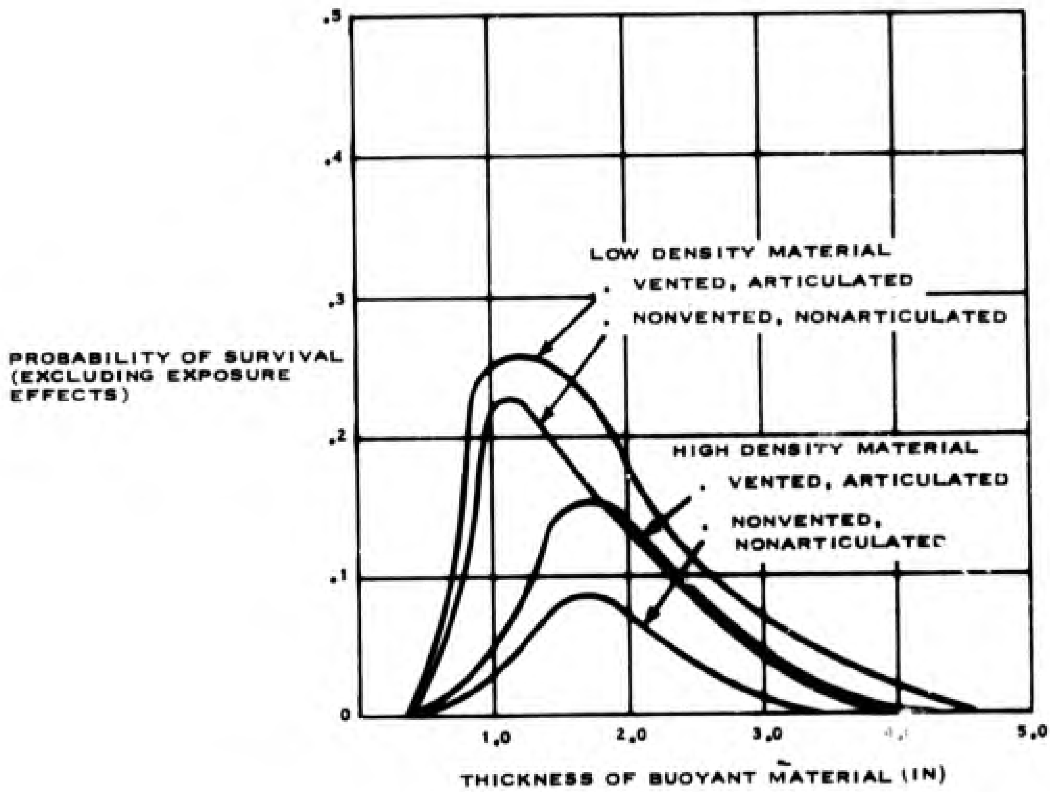


FIGURE III-6. Effects of Material Density, Design, and Thickness upon Short-Term Probability of Survival--Configuration 1

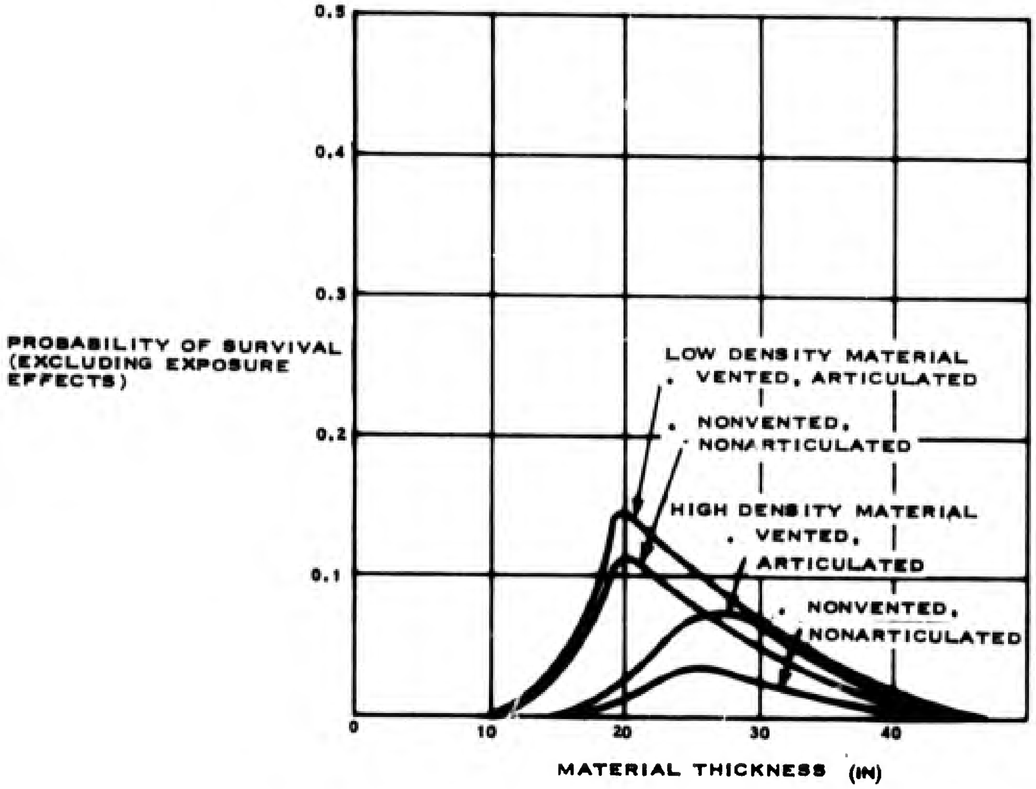


FIGURE III-7. Effects of Material Density, Design, and Thickness upon Short-Term Probability of Survival--Configuration 2

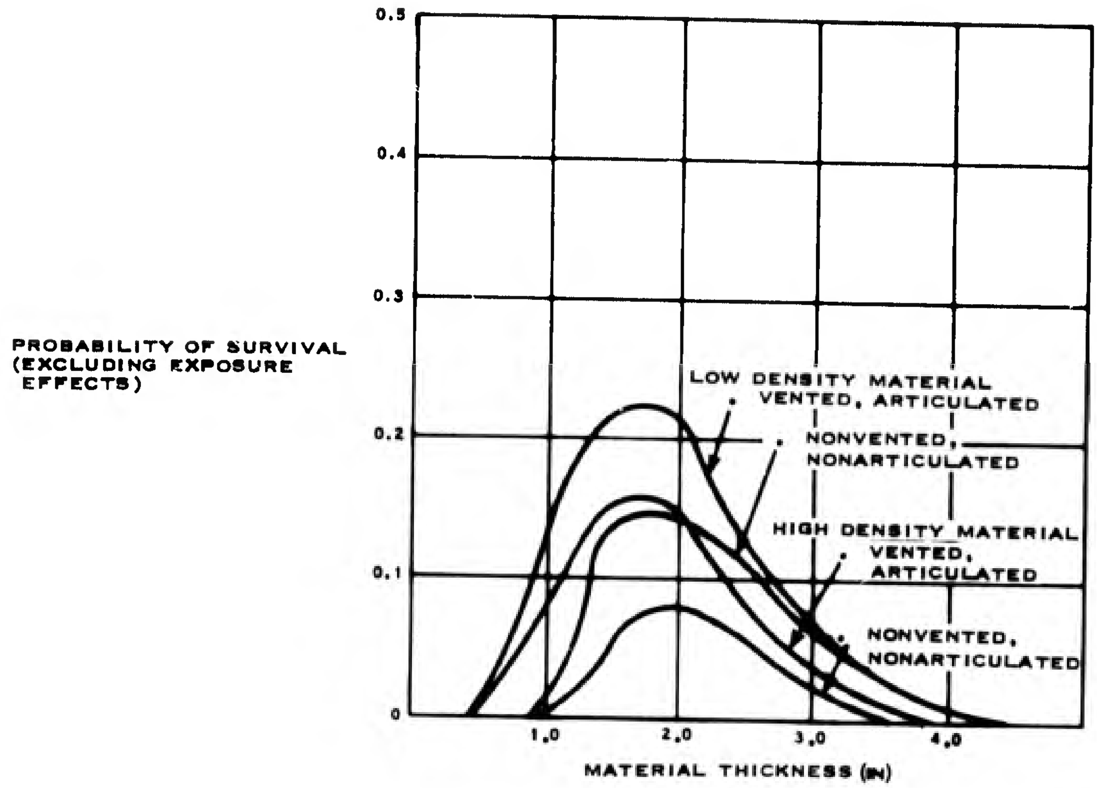


FIGURE III-8. Effects of Material Density, Design, and Thickness upon Short-Term Probability of Survival--Configuration 3

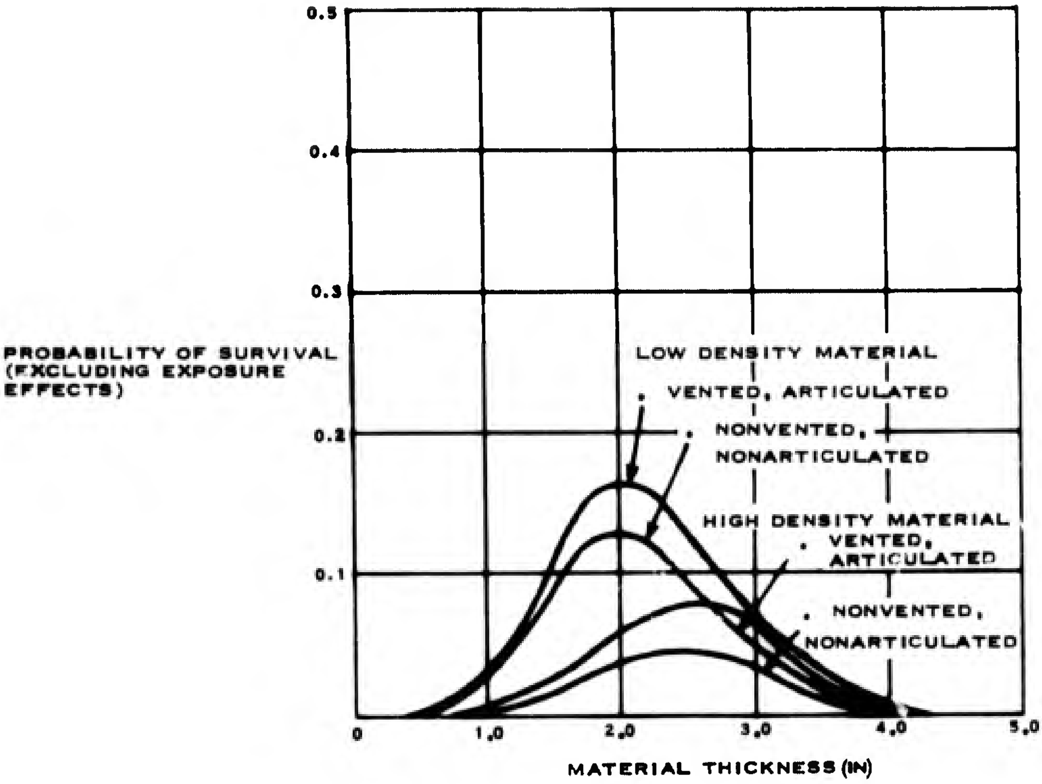


FIGURE III-9. Effects of Material Density, Design, and Thickness upon Short-Term Probability of Survival--Configuration 4

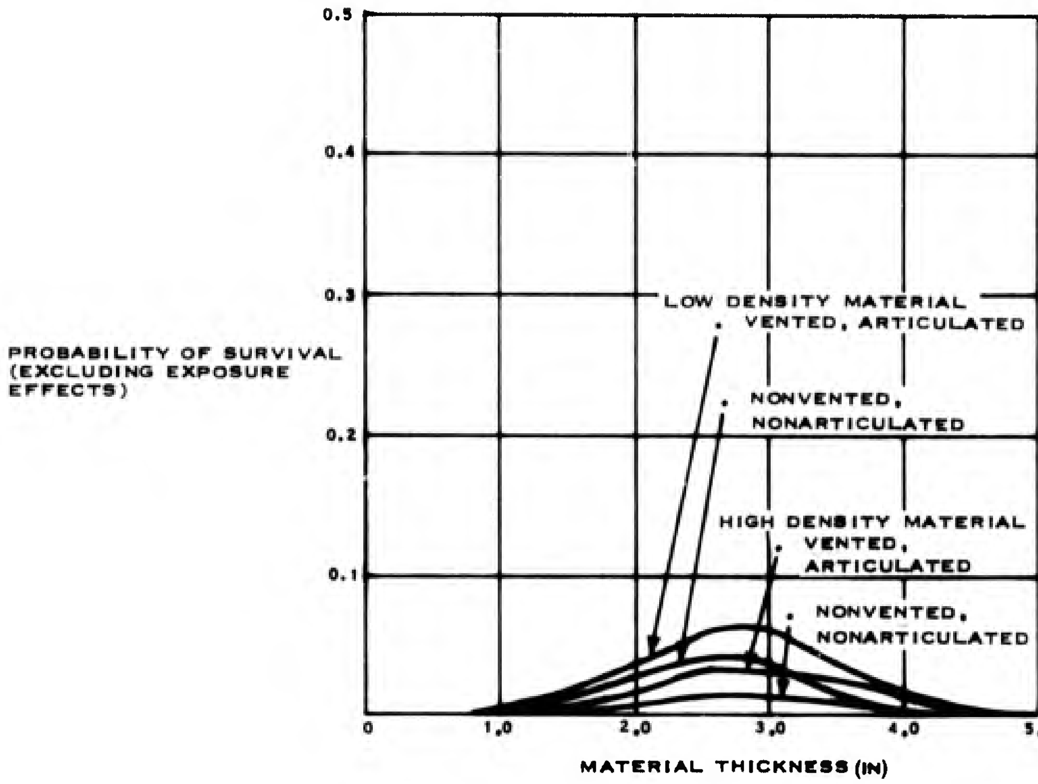


FIGURE III-10. Effects of Material Density, Design, and Thickness upon Short-Term Probability of Survival--Configuration 5

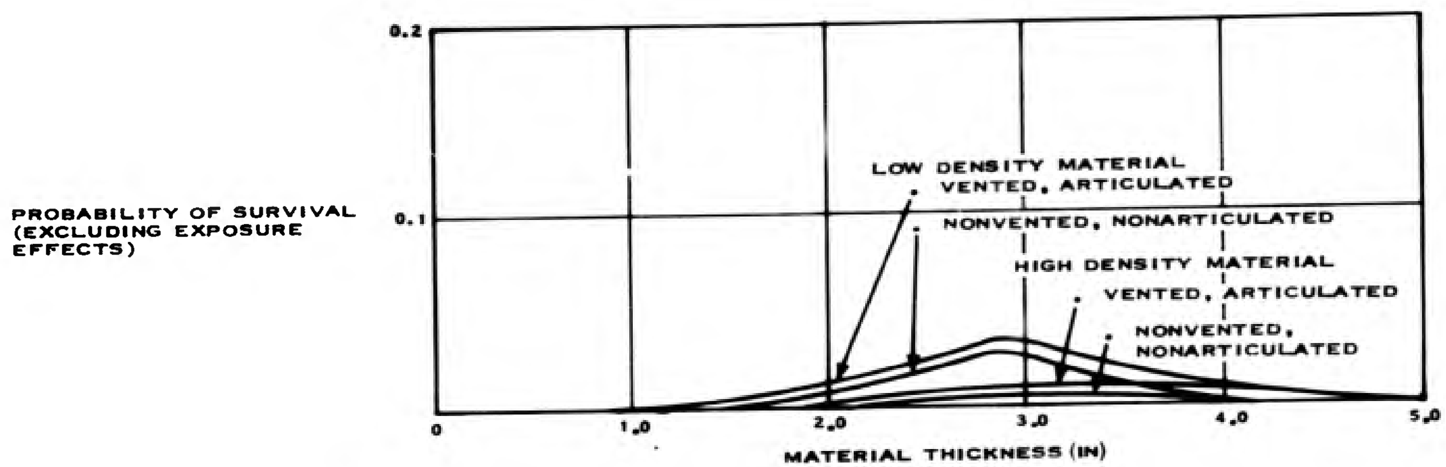


FIGURE III-11. Effects of Material Density, Design, and Thickness upon Short-Term Probability of Survival--Configuration 6

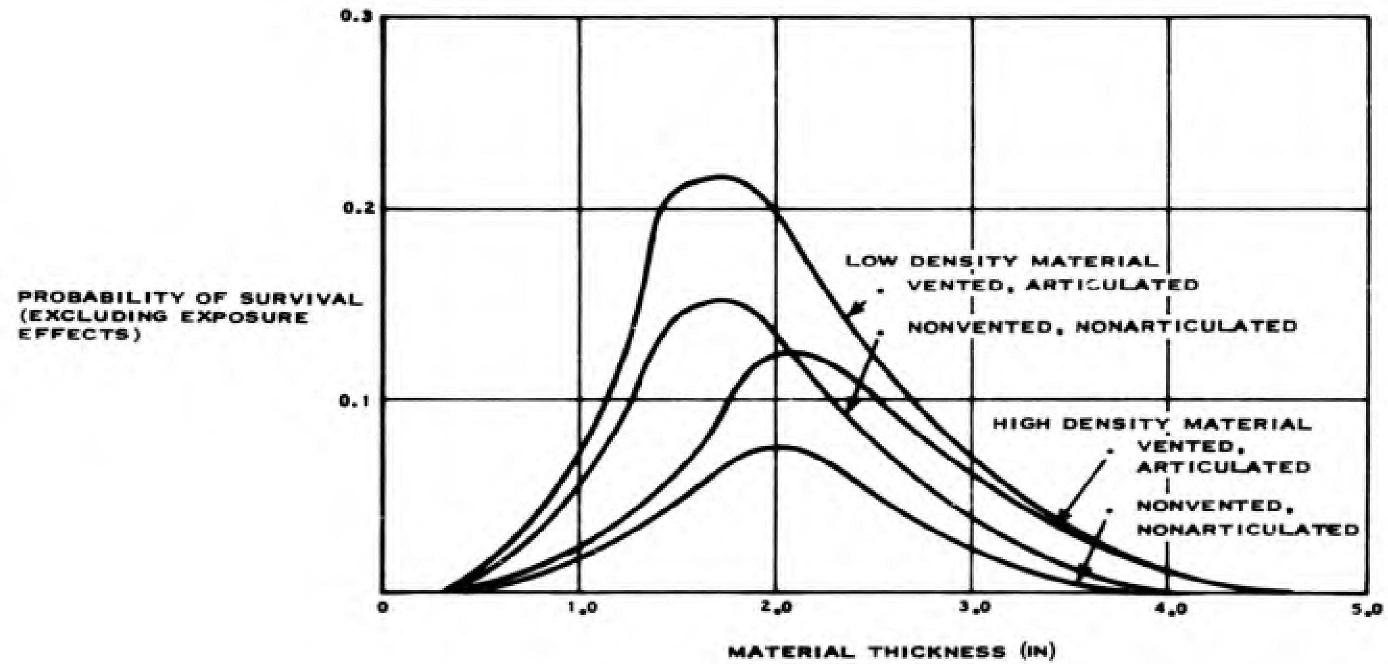


FIGURE III-12. Effects of Material Density, Design, and Thickness upon Short-Term Probability of Survival--Configuration 7

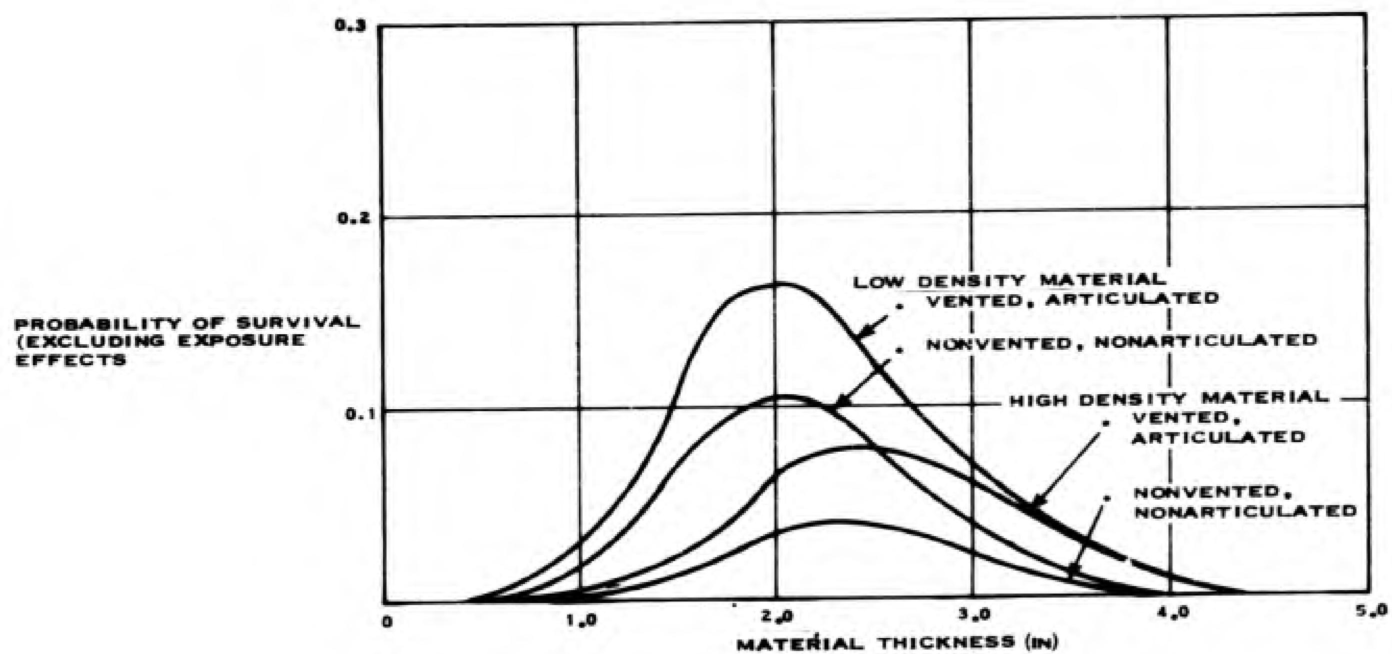


FIGURE III-13. Effects of Material Density, Design, and Thickness upon Short-Term Probability of Survival--Configuration 8

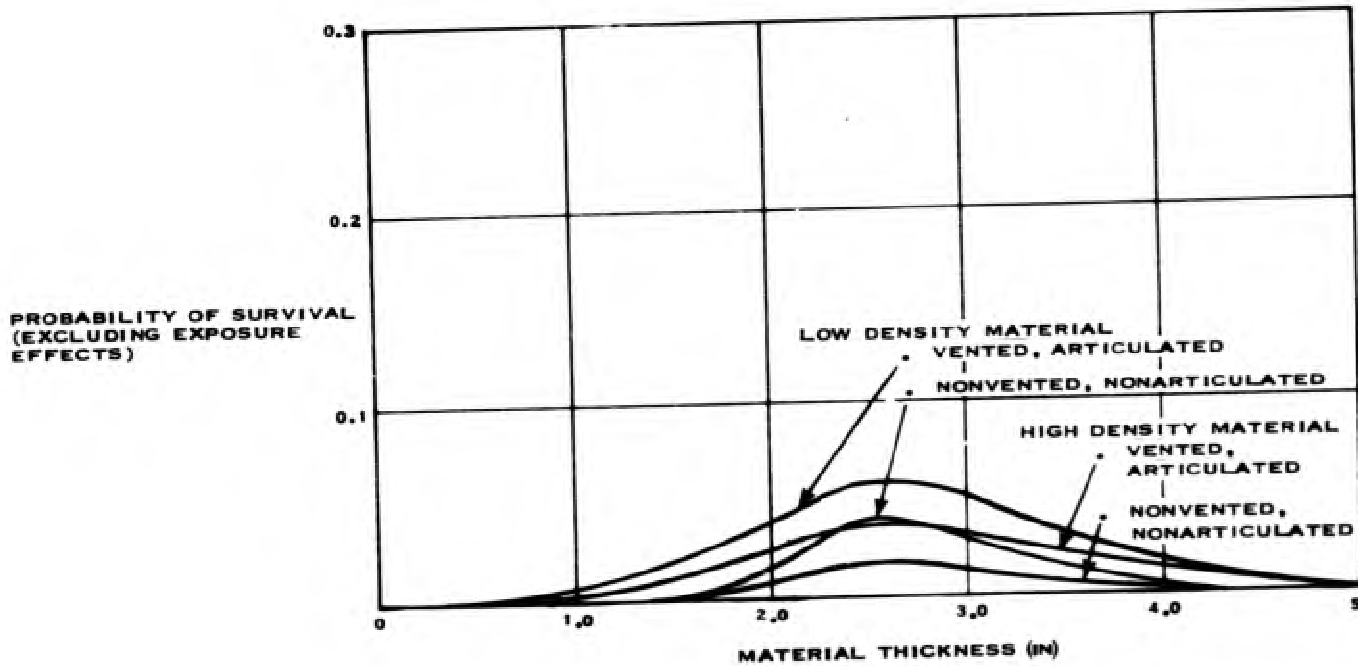


FIGURE III-14. Effects of Material Density, Design, and Thickness upon Short-Term Probability of Survival--Configuration 9

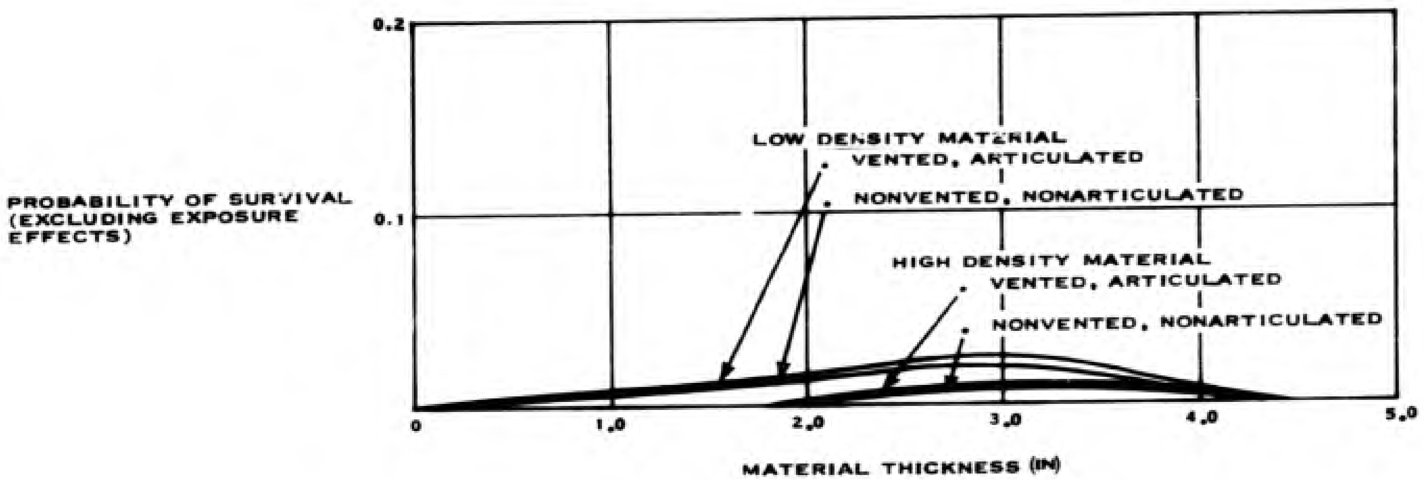


FIGURE III-15. Effects of Material Density, Design, and Thickness upon Short-Term Probability of Survival--Configuration 10

vented design, and the unarticulated, nonvented design, to show the sensitivities of material density and design techniques upon the effectiveness of the configuration.

These figures show that for every configuration analyzed the use of low density material and proper design improve the device, the improvement due to material density change being more than twice as significant as the design effect. These variations are presented in Table III-2.

The analysis also shows that personnel flotation devices using inherently buoyant materials can provide, at best, 26 percent probability of survival. The inflatable PFD can provide the same probability of survival assuming a reliability as low as 50 percent and probability of survival as high as 48 percent if 90 percent reliability is considered.

4. EFFECTIVENESS--TOTAL PROBABILITY OF SURVIVAL

The effectiveness of a jacket-type personnel flotation device is the extent to which it will prevent drowning of persons who enter the water accidentally. This study had excluded the degree to which it will keep the immersed person from dying from the direct effects of water exposure, but did include the effects of exposure, to the extent

TABLE III-2. Impact of Material Density and Design Upon Configuration Effectiveness

CONFIGURATION	DIFFERENCE DUE TO BUOYANT MATERIAL DENSITY		DIFFERENCE DUE TO MATERIAL DESIGN	
	TOTAL % GAIN [1]	RELATIVE GAIN [2]	TOTAL % GAIN [3]	RELATIVE GAIN [4]
1	11	73	2.5	15
2	7.0	94	3.0	26
3	8.0	55	7.5	50
4	8.5	105	3.5	27
5	3.0	100	2	50
6	2.5	250	0.75	27
7	9.0	72	6.5	43
8	9.0	120	6	58
9	2.75	69	3.0	80
10	1.5	150	0.5	25

1 – MAX VALUE OF LOW DENSITY–MAX VALUE OF HIGH DENSITY/MAX VALUE OF LOW DENSITY

2 – MAX VALUE OF LOW DENSITY/MAX VALUE OF HIGH DENSITY

3 – MAX VALUE OF ARTICULATED, VENTED, LOW DENSITY–MAX VALUE OF NON ARTICULATED, NON VENTED LOW DENSITY MAX/VALUE OF ARTICULATED VENTED LOW DENSITY

4 – MAX VALUE OF ARTICULATED, VENTED LOW DENSITY/MAX VALUE OF NON ARTICULATED, NON VENTED LOW DENSITY MATERIAL

that it affected a person's loss of strength and, eventually, consciousness. A jacket-type personnel flotation device should maintain a person in a safe body attitude when he has become either weakened or unconscious. Persons wearing jackets which do not maintain them in a safe attitude

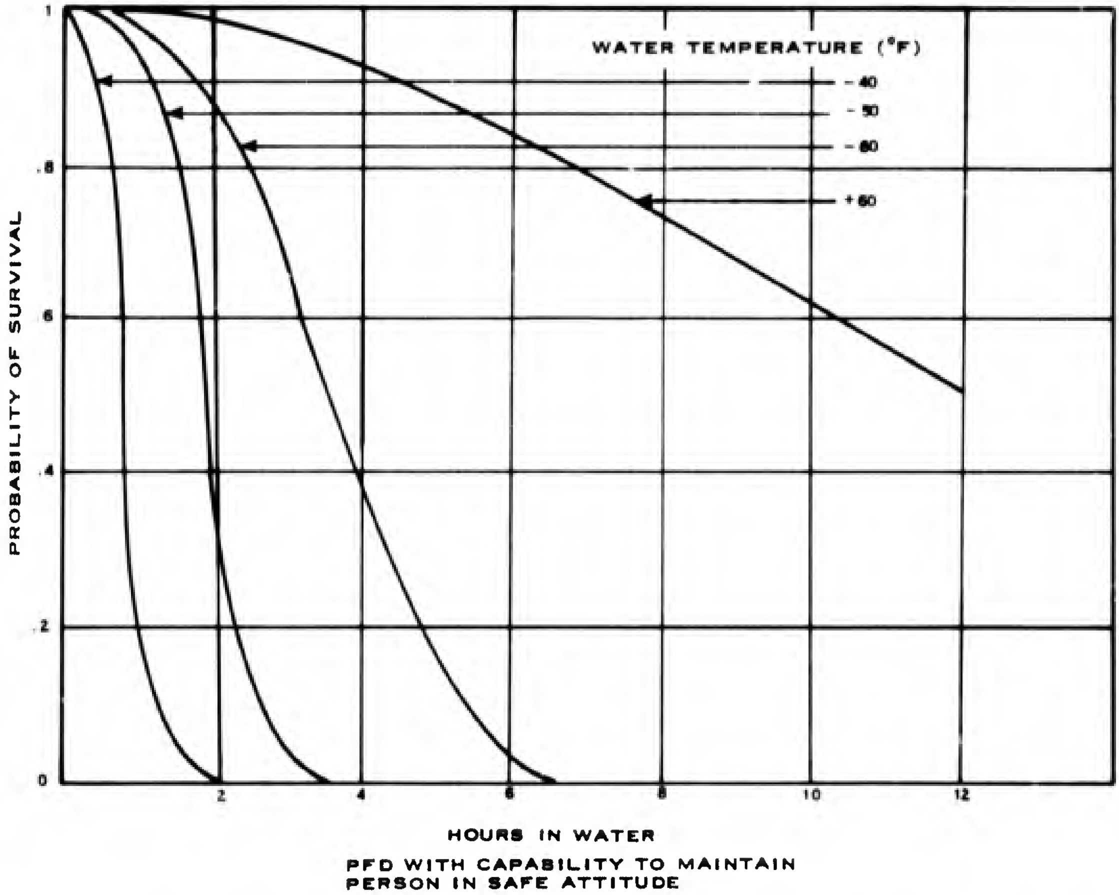


FIGURE III-16. Probability of Survival Using PFD With Safe-Attitude Capability

are assumed to drown after becoming excessively weakened or unconscious. The probabilities of survival when using a jacket which does maintain a person in a safe attitude are shown in Figure III-16, while the probabilities of survival using a jacket which does not provide a capability to maintain a safe body attitude are shown in Figure III-17. These values were derived from data presented in the Appendix (2).

An analysis was made to determine the effectiveness of the different configurations when the exposure effects were considered.

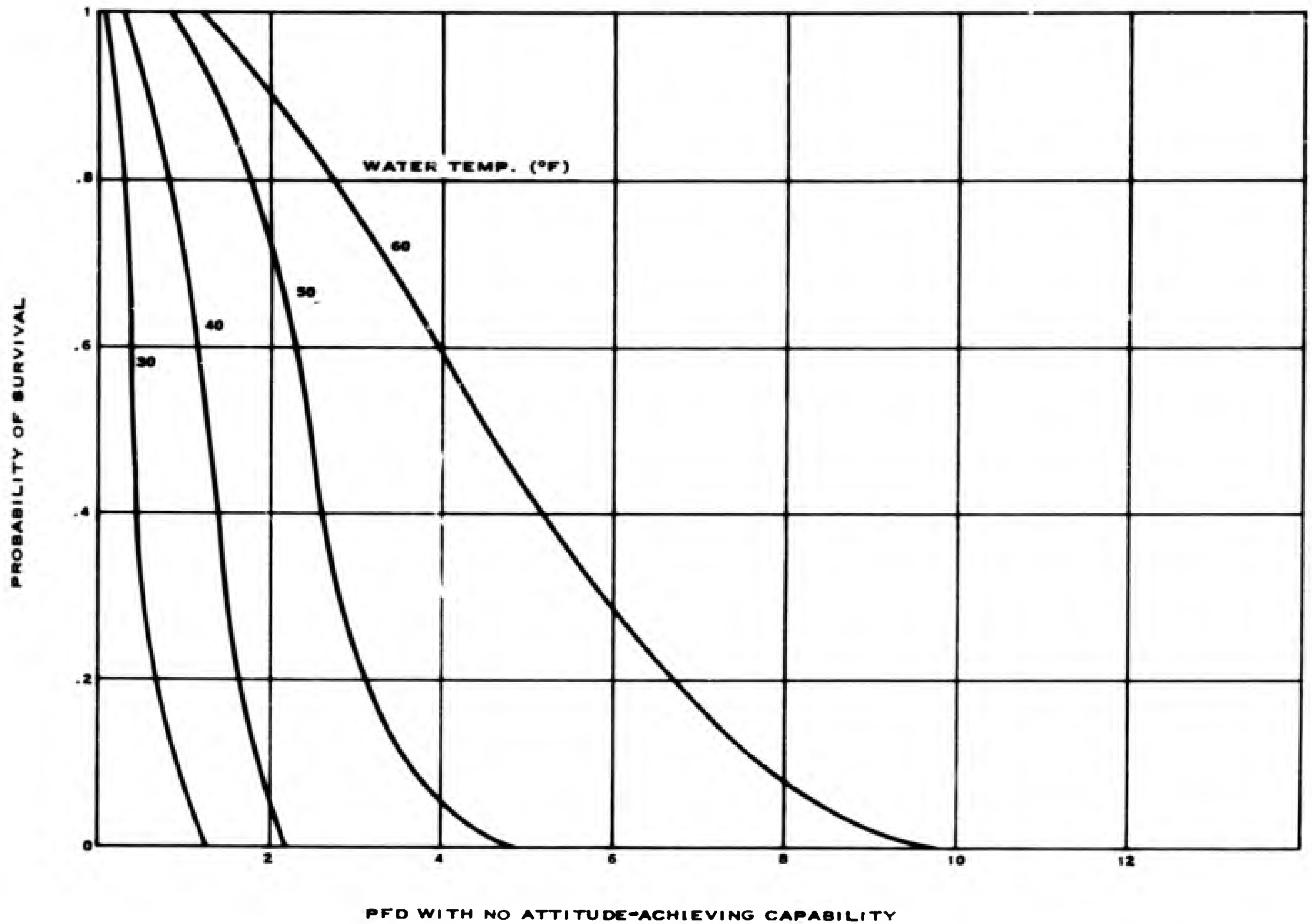


FIGURE III-17. Probability of Survival Using a PFD Without Safe- Attitude Capability

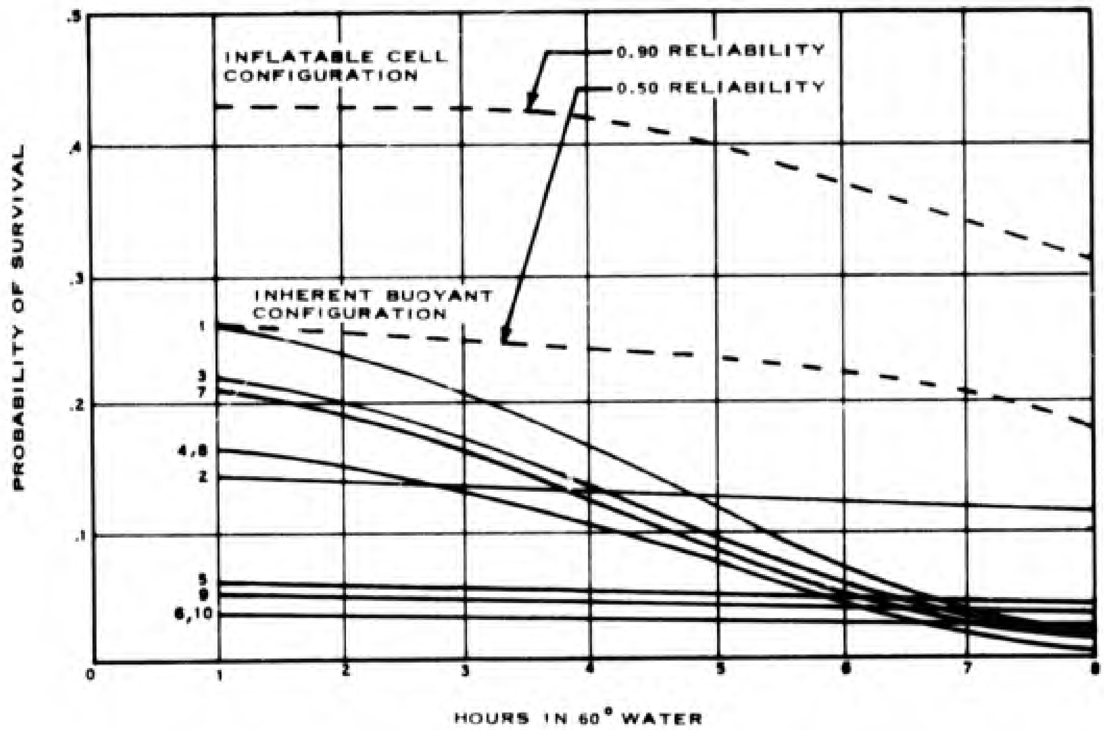


FIGURE III-18. Probabilities of Survival Using Different Jacket Configurations - Warm Water

In this analysis, the maximum short-term probability-of-survival values were used for each configuration. These values were multiplied times the survival values of Figure III-16 if the configuration was one in which the body would be maintained in a safe attitude (configurations 2, 5, 6, 9, 10, and 11). When the configuration would not maintain the body in a safe attitude (configurations 1, 3, 4, 7, and 8 with no straps), the values in Figure III-17 were used, together with the maximum short-term probability-of-survival values. The results are shown for different water-temperature conditions in Figures III-18, 19, and 20. A further analysis of these data, shown in Figure III-21,

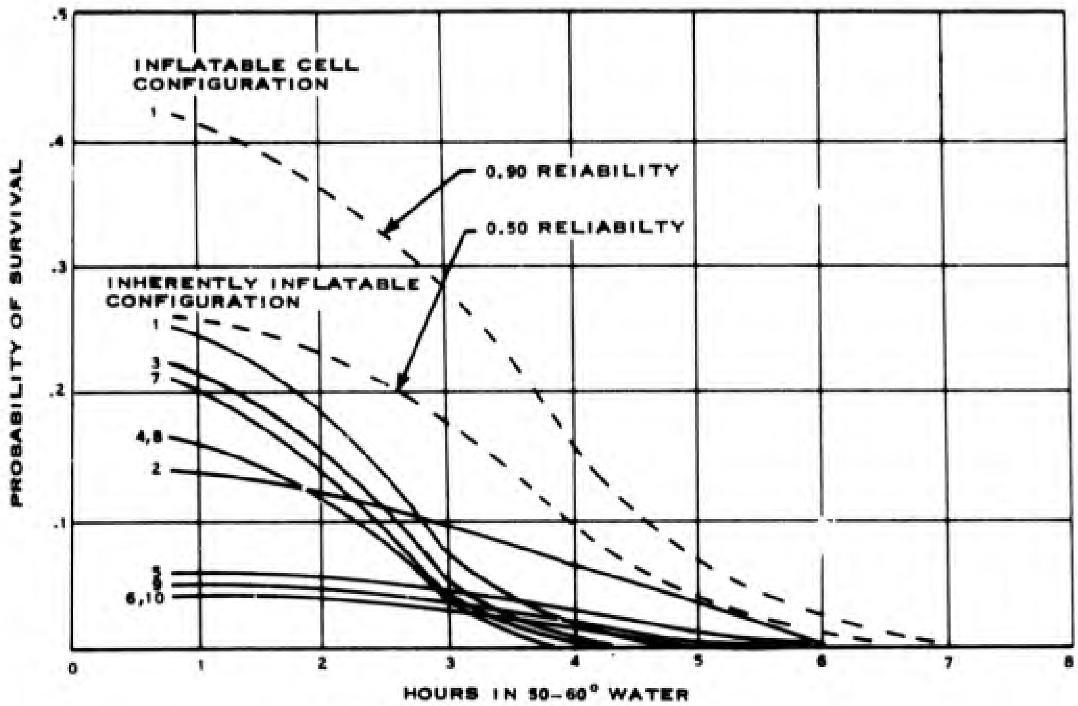


FIGURE III-19. Probabilities of Survival Using Different Jacket Configurations-Cooled Water

shows the differences in probability of survival (P_S) between the best inherently buoyant jacket providing a safe attitude and the best jacket which does not. It can be seen that no firm conclusion can be drawn without inferring an average time to be rescued (time in water) and/or water temperature limitation. Finally, an analysis was made comparing the inflatable jacket-type personnel flotation device to the best inherently buoyant jacket which did not provide a safe attitude. The results are shown in Figure III-22. It can be seen that the results show the inflatable personnel flotation devices are superior, never inferior, to the inherently buoyant devices in almost all cases, even when an extremely low reliability (0. 50) is assumed for the inflatable PFD.

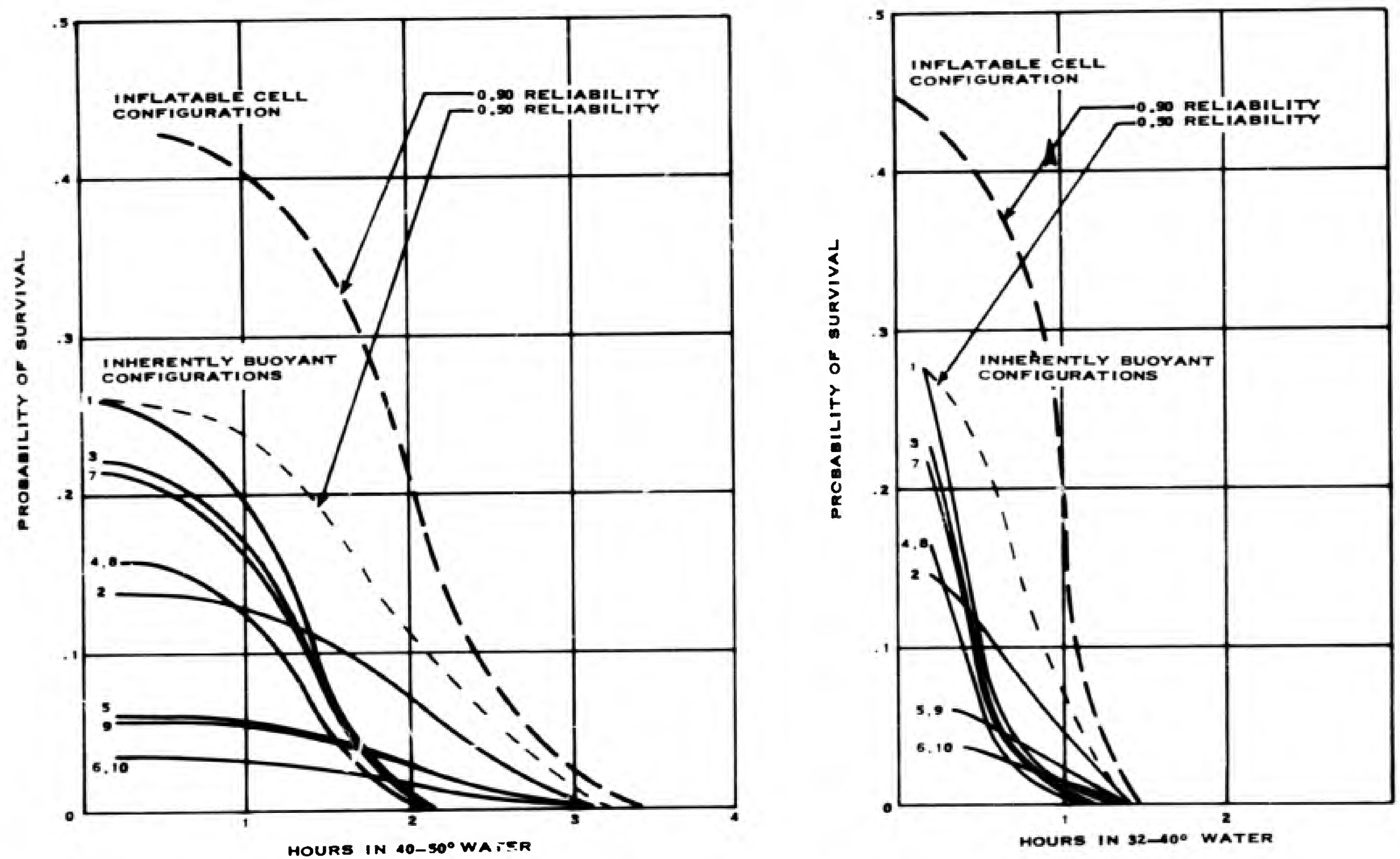


FIGURE III-20. Probabilities of Survival Using Different Jacket Configurations-Chilled Water

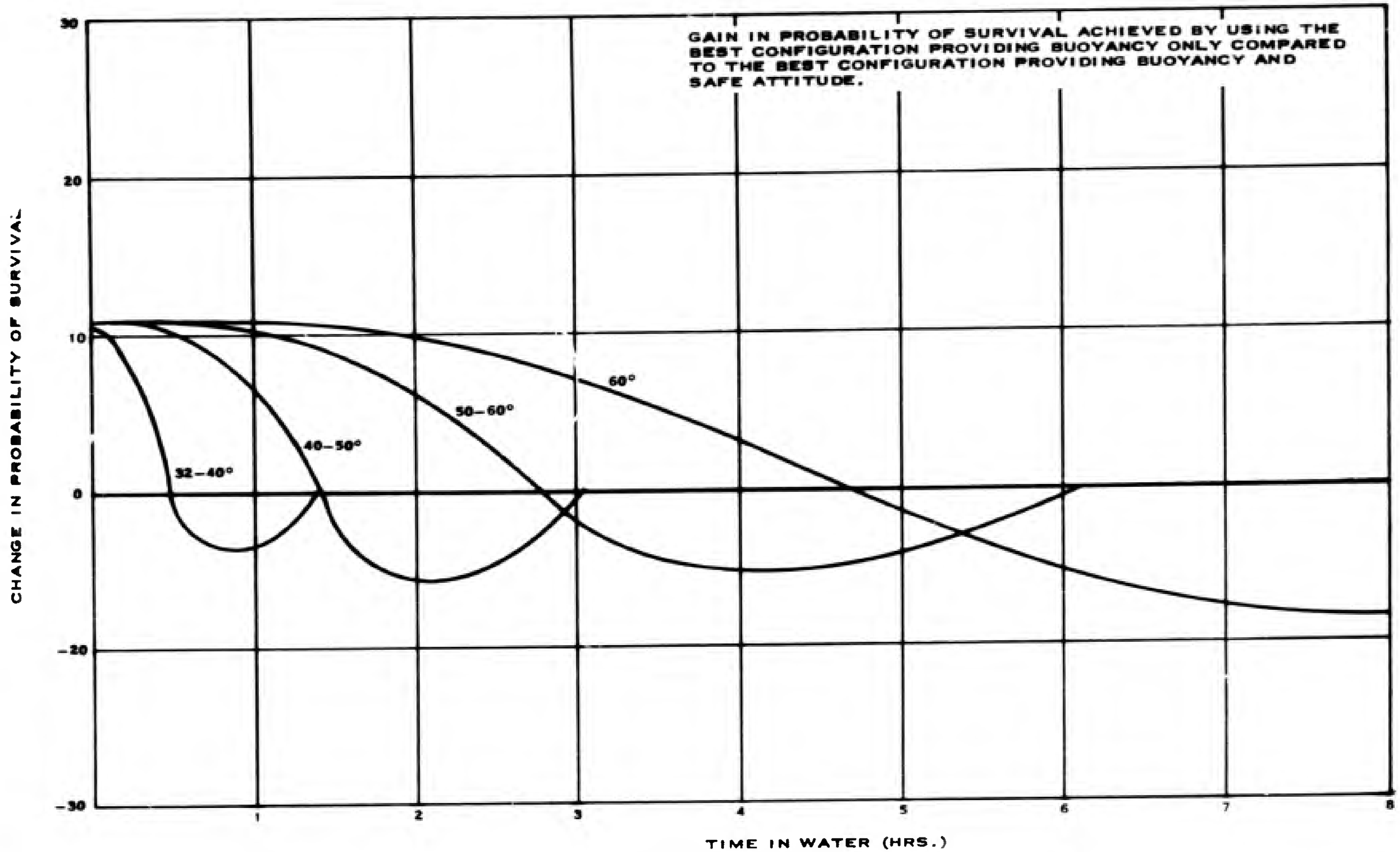


FIGURE III-21. Advantages of More Wearable Jacket-Type PFD

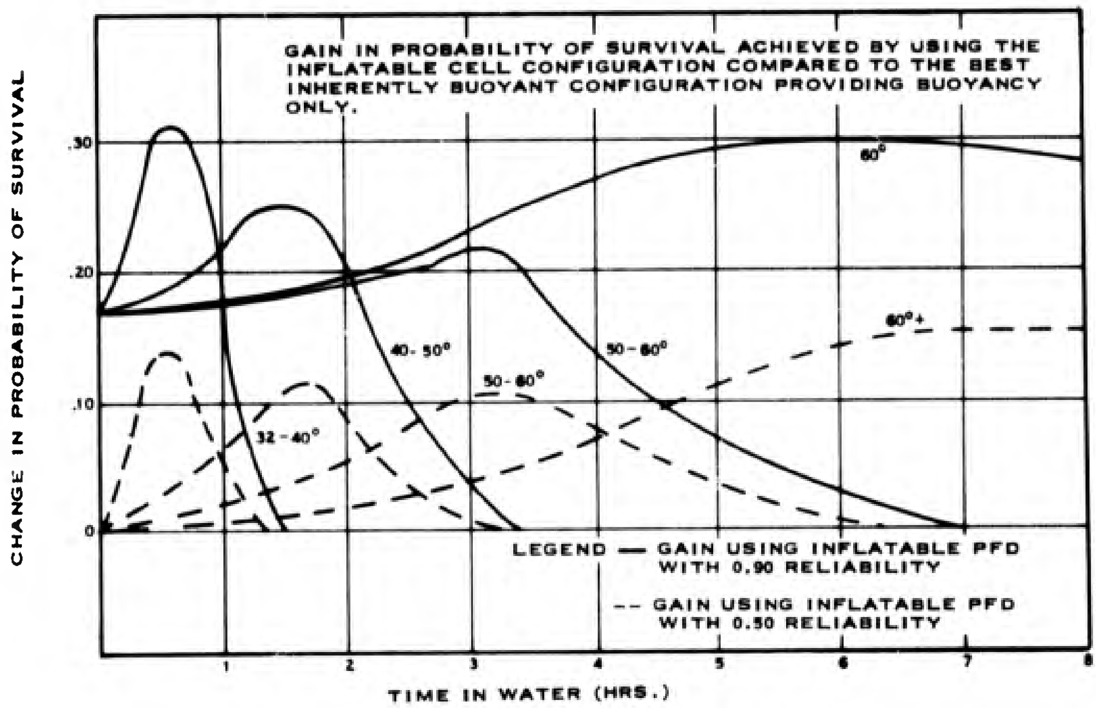


FIGURE III-22. Advantage of Inflatable Jacket-Type PFD

5. CONCLUSIONS

Any conclusions drawn from the study must be tempered by the fact that many of the assumptions basic to the trade-off and effectiveness study have not been validated. The relationships between a jacket's wear acceptance and its characteristics are imperfectly known. Every effort was made, within the confines of this study, to develop what appeared to be reasonable relationships; however, relatively minor changes in these assumptions could have a significant impact upon results obtained or conclusions drawn from the results. Within these conditions, the following conclusions can be drawn.

(1) <u>Superior Effectiveness of Inflatable Personnel Flotation Devices</u>

A jacket-type personnel flotation device which uses an air-inflatable cell is superior to any jacket using inherently buoyant material, despite its less-than-perfect reliability. The basic reason for this superior effectiveness is that it can be configured, when not inflated, into a jacket design which should have a good wear acceptance without sacrificing available buoyancy or the capability of maintaining the person in a safe body attitude. Any jacket device configured to achieve a good wear acceptance must sacrifice either available buoyancy and/or the capability to achieve a safe attitude.

(2) <u>Attitude-Achieving Capability of a Jacket-Type Personnel Flotation Device</u>

It is difficult to draw any firm conclusions with regard to the relative difference in the effectiveness of a jacket which will be worn by more people but which does not provide a safe attitude, contrasted to a jacket which provides the safe attitude but will be worn by fewer people. The superiority of one type over the other is conditional upon the water temperature and the time the person will be in the water. If the water temperature is between 40 degrees and 50 degrees F, and if the person will not be in the water longer than an hour and fifteen minutes, the more wearable jacket is superior. If the water temperature is between 50 and 60 degrees F, the more wearable jacket is superior up to about 2-1/2 hours of exposure. However, when the water temperature is 40 degrees or less, the jacket providing a safe attitude is superior if the person is in the water more than one half hour.

These data can be roughly translated into the following rules:

1. When the water temperature is low and rescue could take a considerable time, a personnel flotation device which provides a safe attitude is superior.

2. When the water temperature is higher and exposure is limited, the more wearable but adequate device as defined in Page II-43 is superior.

It could be inferred from the above that merchant ships, and probably ships for hire, should use jackets which provide a safe attitude capability. Pleasure craft should probably use a more wearable jacket. This preceding discussion was based on personnel flotation device jackets which used inherently buoyant material, rather than inflatable cell(s). If the latter type of flotation device were found acceptable with respect to state-of-the-art problems, it would resolve this dilemma of safe attitude versus wear acceptance.

(3) Relative Merit of Throw-Type Devices

The low effectiveness shown by most of the jacket-type personnel flotation devices forces a reexamination of the throw-type devices. The throw-type devices have been considered an ancillary device; however, it would appear that more attention should be paid to them, since the jacket-type devices appear to have such a low effectiveness that any ancillary techniques gain in importance.

A direct comparison of the jacket- and throw-type personnel flotation devices is difficult, since different factors define their availability. The availability of the throw-type device is dependent upon the time to access and throw, throwing distance, accuracy, and ship's speed, as well as the nature of the accident. If a buoyant cushion can normally be thrown a distance over 100 feet in less than ten seconds from the time of an accident involving a person falling overboard and be thrown with an accuracy of better than 50 feet, it would have an effectiveness about equal to a jacket-type device. It is unlikely that a buoyant cushion could be thrown that distance with that accuracy, and it is only barely possible that a ring could be thrown that well.

IV. STATE-OF-THE-ART ASSESSMENT

1. SUMMARY

Discussions were held with a number of the basic suppliers to the manufacturers, as well as the manufacturers and distributors of personnel flotation devices. In addition, a number of reports related to the state-of-the-art (SOA) in personnel flotation devices were reviewed. On the basis of these activities and the results of the preceding sections of this study, the following summarizes the SOA survey.

(1) Buoyant Materials

Buoyant materials were divided into three basic types: inherently buoyant materials, trapped-air materials, and inflatable cells. The following summarizes the assessment of these materials.

1. Inherently Buoyant Materials

Inherently buoyant materials are closed-cell, low-density substances. Currently, the prime materials used are the foam plastics. The lighter the substance, the better its qualifications; however, it must be soft, nonfriable, and have a low water absorption rate. This restricts the candidates to polyvinyl chloride (PVC) foam, which has a density higher than desired, but is relatively soft, and polyethylene foam, which is light but is not very soft. There do not seem to be any new closed-cell materials under development which would appear to offer any challenge to PVC or polyethylene foam. There is very little that can be done to make PVC lighter; however, there are a number of things that can be done to polyethylene to make it less stiff--i.e., the material can be configured to have lowered moments of inertia by using it in a number of overlaying thin sheets rather than utilizing it in a single slab. Recently there has been some activity along this line by some of the personnel flotation device manufacturers. However, there has been very little imaginative effort by the manufacturers to improve the characteristics of polyethylene.

2. Trapped-Air Materials

Trapped-air materials are substances which, in their designed or natural state, tend to retain a large percentage of air. Fibrous materials, such as kapok or spun glass, are examples of conventional trapped-air materials. However, materials specially developed for, and currently used in the packing of, personnel flotation devices should be included as trapped-air materials. These packing materials consist of two sheets of film plastic with many trapped-air cells between the sheets. The specially developed materials consist of small air pillows formed by heat-sealed plastic film bags containing air under slight atmospheric pressure. There has been relatively little development in these latter types of trapped-air materials, despite their attractive qualities: light weight and flexibility. The conventional trapped-air materials, while extremely flexible, suffer from having relatively high densities. All trapped-air materials are not inherently buoyant and can lose buoyancy from prolonged rough handling or, in the case of kapok or spun glass, from agitation in water. This latter weakness may be a serious deficiency.

3. Inflatable Cells

Induced by military application, there has been considerable activity in product improvement in the area of inflatable cells. At the present time, there are a number of designs which appear to overcome many of the original objections to inflatable devices--i. e., sensitivity to handling and stowage and low reliability. One aspect which has not been well resolved is that of foolproofing the activating gas cartridge(s) to ensure that they are always unused. This problem will probably never be perfectly resolved, but substantial improvements should be readily obtainable.

(2) Jacket-Type Personnel Flotation Devices

Two facts emerge as overriding features of jacket-type PFD's. The general public will overwhelmingly buy the cheaper product and, although purchased, few people will wear the device. The first feature has a major implication in that any improvements which can be made with respect to a jacket should not significantly increase the manufacturing costs. Conversations with several manufacturers of PFD's indicate a strong belief on their part that some jackets of lower price do not conform to United States Coast Guard specifications, despite their bearing the seal of approval. This condition, if true, creates an extremely unfortunate condition for the ethical manufacturers, as well as the entire area of water safety.

A survey of the jackets now sold to the pleasure-boating groups shows a wide range in types, ranging from the yoke type, which is eminently safe and approved by the U. S. Coast Guard, to jackets which contain a thin layer of foam plastic over much of their area, and which are not safe and not yet approved but appear more acceptable to users. The fact that there is a fairly good market for many jackets which are neither U. S. C. G. approved nor inexpensive, but are attractive and comfortable, could indicate that the public is more concerned with comfort and aesthetics than safety. It would appear that either all PFD manufacturers should be periodically inspected or that the lower priced devices be purchased by the U. S. C. G. and sent to the Yacht Safety Bureau for testing to insure compliance with U. S. C. G. requirements.

(3) <u>Throw-Type Personnel Flotation Devices</u>

There are very few throw-type personnel flotation devices, since almost all conform to U. S. C. G. specifications. There are a few of these devices developed during the last several years which are not approved but are intended to be thrown as rescue aids. However, the differences among approved and non-approved devices are minor, and the area appears to be static.

Many improvements appear possible but there has been no significant activity among the manufacturers.

(4) Special Personnel Flotation Devices

A few special personnel flotation devices exist which are not U. S. C. G. approved, and do not fall into the realms of any of the three preceding types of devices. These devices are small, can be worn or carried by the person, and can be activated into an air-filled cell when the person enters the water. Their advantages are user acceptance and high availability, while their disadvantage is their questionable safety and reliability.

2. FLOTATION MATERIAL ASSESSMENT

A study was conducted of buoyant materials and of buoyant vests to determine whether more acceptable and more available vests could be configured.

A survey was made of flotation materials, with particular emphasis on currently available foam plastics. The results of this survey did not reveal any materials which appeared superior to the approved foam plastics--e. g., polyvinyl chloride (PVC) and polyethylene.

The survey consisted of reviewing existing pertinent literature, discussions with personnel from Dupont, Dow, and Union Carbide, as well as meeting with flotation material/devices manufacturers such as Goodrich, Atlantic and Pacific Manufacturing Company, and others.

The use of foam plastics for flotation devices constitutes a very small percentage of the foam plastic market. It appears that the manufacturers of both the resin and blowing agents, and the manufacturers of the foam plastics, have not made any significant effort to devise new materials or applications of existing materials for the personnel flotation device market.

The vast majority of foam plastics falls into one or two categories:

(1) Soft, open-cell materials which have unacceptable water absorption characteristics

(2) Rigid, closed-cell materials whose flexural and compressive strengths are in excess of acceptable limits for life preservers as previously established.

Although new materials are being developed, none of the data on these materials could offer any advantages over the existing approved unicellular foam plastics. Table IV-1 shows survey results of a number of the materials examined.

TABLE IV-1. Summary of Acceptability of Buoyant Materials

Material \ Property	Density	Water Absorption	Compressive Strength	Cohesion/Wall Strength	Flammability	Unacceptable	Marginal	Acceptable
Polyurethanes – CC			x	x		x		
Polyurethanes – OC		x				x		
Cellulose acetate	x	x	x	x	x	x		
Phenolics		x				x		
Polystyrenes			x	x		x		
Silicons	x		x	x		x		
Polychloride – CC								x
Polychloride – OC		x			x	x		
Polyethylenes			x				x	
Polypropylene	x		x	x		x		
Neoprene	x		x			x		
Kapok		x			x	x		

Legend

CC – Closed cell

OC – Open cell

In addition to the survey of foam plastics, an examination was made of kapok since (1) it is used more than any other material in buoyant vests, and (2) it appeared to have certain disturbing properties. Although no firm statistics were available, it appears that over 75 percent of all buoyant vests sold contain kapok. While kapok is certainly the most comfortable material and meets the U. S. C. G. requirements, it appears that the main reason for its success is its sales price; buoyant vests containing kapok cost substantially less than vests containing foam plastic.

The buoyant material used in personnel flotation devices should possess the following properties:

- Low density
- Low water absorption
- Low compressive strength
- Low flexural strength
- Good cohesion and cell-wall strength
- Nonflammable or a slow burn rate.

These properties of various flotation materials are discussed in the following pages.

(1) Density

Any material whose density is less than that of water is theoretically an acceptable material; however, the lighter the material, the better it is for use in buoyant vests. The Coast Guard has specified five pounds of the foam plastic per cubic foot. There are a number of materials having a lower density, such as the styrofoams and urethanes; however, their other undesirable characteristics (Appendix A, Section 9) exclude them from consideration. These materials typically tend to be friable or crushable or both.

The amount of material required to achieve a positive buoyancy is equal to the difference in density between water and the material times the volume of the material.

(2) Water Absorption

Water absorption is the amount of water absorbed into the material's cavities or cells per unit time. In general, the property is obvious, but in the specific application to flotation devices, it is not a simple property to quantify.

An inherently buoyant material is one which can suffer a large number of punctures without a significant increase in water absorption rate of loss of buoyancy such as a closed-cell foam plastic whose cells are small. Most other trapped-air devices such as inflatable bladders or cells would rapidly lose buoyancy after a limited number of punctures. Kapok is basically a trapped-air material. The air is entrapped among the fibers in such a way that kapok behaves in a manner comparable to the semiopen-celled materials. When encased in a watertight container, kapok, unlike air, can tolerate a puncture (or rupture) without degrading the entire assembly.

One fairly recent innovation in plastics is the use of film plastic to make trapped air structures. The most common use is packing material. A derivation of this is the Flotherchoc jacket which is manufactured in France. The buoyant material is air, trapped in film PVC bags. The inflated bags are approximately 2" x 1" x 0.75" thick. A vest will contain several hundred of these bags. While any one cell can be punctured and, therefore, lose its buoyancy, the likelihood of a significant number of them being simultaneously punctured is very low.

Kapok, as previously stated, is basically a trapped-air system. The air will remain entrapped so long as the water pressure differential does not become too small. A study conducted of the water absorption of kapok consisted of immersing test pads of kapok, four inches in diameter and of varying lengths in a tank of still water, two feet deep. The bottoms of the pads were kept two inches from the tank bottom; the cylindrical pads were floated so that their long axis was vertical. It was found that the longer the cylinder, the greater the water absorption--i.e., a 10-inch long cylinder absorbed 4.5 inches of water in 24 hours, while a 16-inch long cylinder absorbed 9 inches of water. Water absorption for kapok, in still water, is a function of the vertical length of the material; the longer the section, the greater the absorption. Figure IV-1 illustrates the results obtained.

Other studies performed by Mellon Institute in conjunction with the U. S. Navy were made of kapok when either the water or the kapok was agitated. Varied results were obtained depending on the nature and degree of the agitation It appears from these results that kapok could lose its buoyancy rapidly when the wearer of a kapok vest is active in the water, particularly when the material is alternately compressed and allowed to

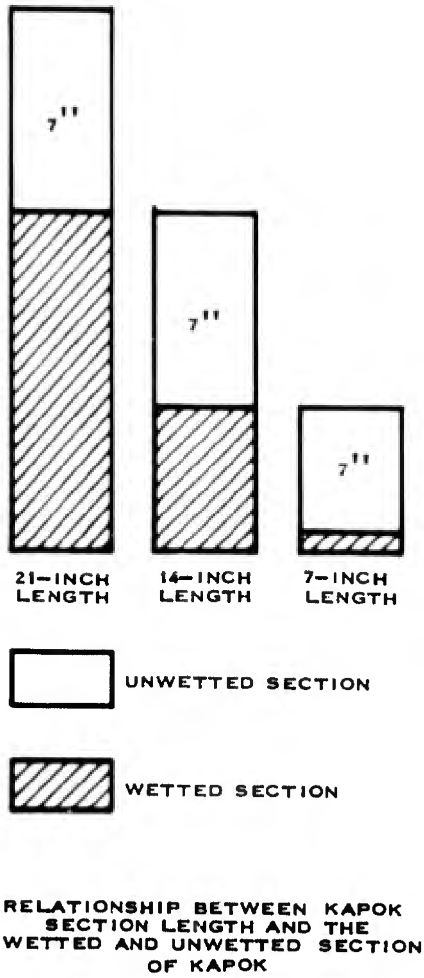


FIGURE IV-1. Relationship Between Kapok Section Length and the Wetted and Unwetted Sections of Kapok expand in the water. Figure IV-2 shows the percentage residual buoyancy of PVC, polyethylene, and kapok as a function of time in the water. The results for kapok in agitated conditions are based upon fragmentary data.

In summary, unicellular materials generally have excellent water absorption characteristics and are inherently buoyant. Other materials have absorption rates which are dependent on how they are shaped and used and the permeability of the container. Open-cell plastics, in any arrangement, are unsatisfactory. Since the experimental data on kapok is fragmentary further testing is required before firm conclusions can be reached. A PFD system consisting of small trapped-air cells is acceptable because of its inherently high reliability, since there is limited likelihood that a significant proportion of these cells would be punctured simultaneously. Inflatable air cells are not generally acceptable because of their inherently low reliability, since only a small number of independent cells can be used. Currently available materials and designs can significantly reduce the possibility of self-puncture.

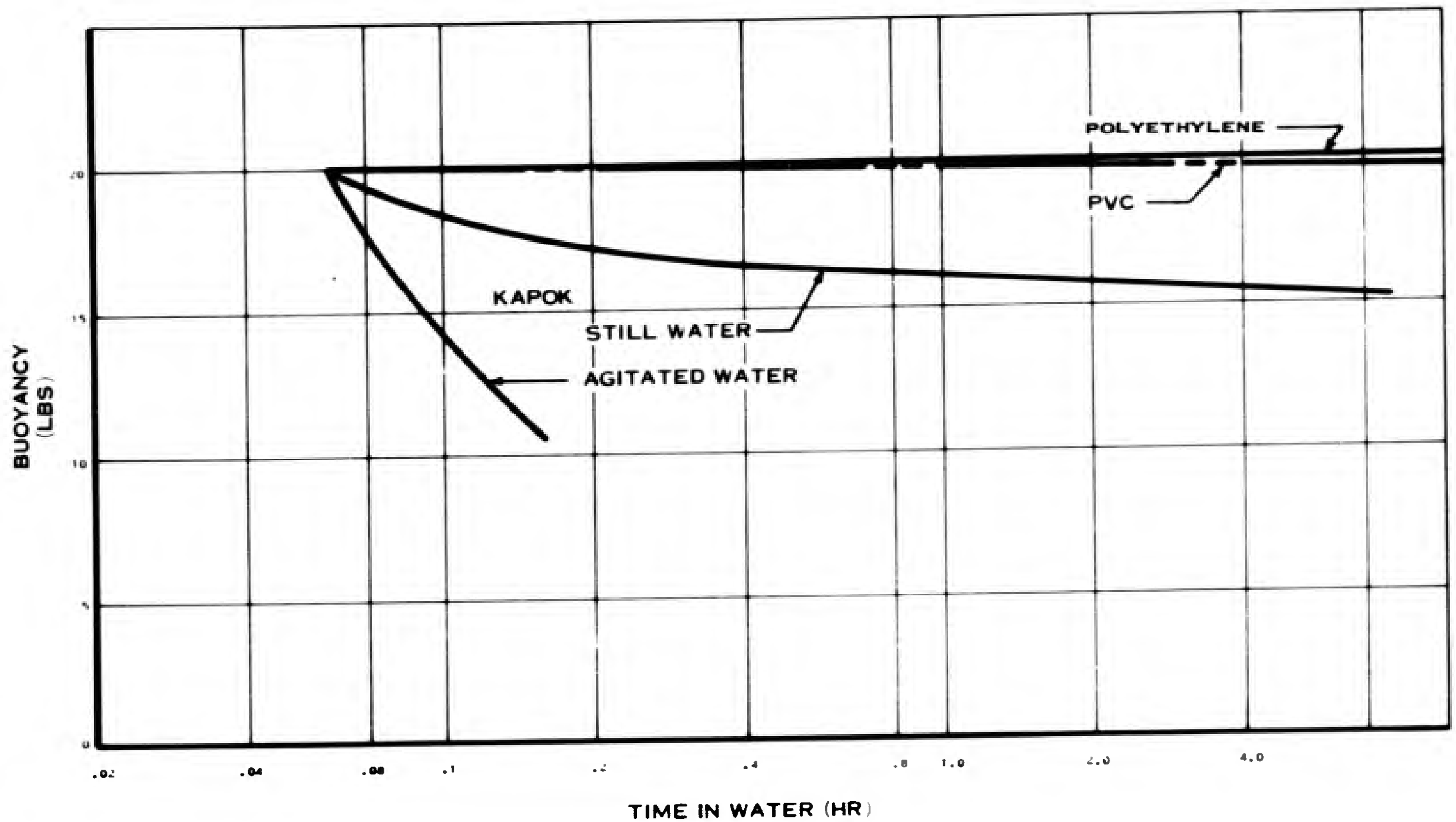


FIGURE IV-2. Changes in Buoyancy With Time and Due to Agitation

(3) Compressive Strength

An ideal life jacket material should be soft and thus have low compressive strength. Open-cell materials can have a very low compressive strength such 0.2 psi to achieve a 10 percent deflection of material, while many closed-cell materials have a very high compressive strength, i.e., over 100 psi per 10 percent deflection. PVC has a compressive strength of about 8 psi per 10 percent deflection.

There are two basic reasons for wanting a low compressive strength: safety and freedom of movement. Incidents have occurred in which necks were broken and breasts sheared off when passengers, wearing cork or wood life preservers, jumped off ships. These injuries would not have occurred with a buoyant material of lower compressive strength. Secondly, a buoyant vest should not be so stiff as to restrict the freedom of motion. Compressive strength is an attribute of stiffness of a material which, together with its moment of inertia and hysteresis, defines the amount of energy required to dynamically alter the shape of the material--i.e., to bend and compress the material while engaged in shipboard or swimming activities.

Most closed-cell materials fail to meet these requirements, while most open-cell materials are satisfactory. Discussions were held with manufacturers to determine whether partially closed-cell materials could be made so as to relax their compressive strength properties. However, it appears that this cannot be done.

(4) Flexural Strength

Flexural strength is closely related to compressive strength except that it involves the physical shape of the material such as its moment of inertia.

Flexural strength is not required for safety as much as for freedom of motion. Freedom of motion can be partially achieved independent of the material by shaping the vest so that most arm and trunk movements can be performed without requiring flexure of the buoyant material. However, a vest so configured tends to appear bulky and unattractive.

Very little data exist on the flexural strength of hysteresis of the foam plastics. It is closely related to compressive strength, and any material which has acceptable compressive strength can be assumed to have acceptable flexural strength.

(5) Cohesion and Cell-Wall Strength

Cohesion is the molecular bonding of a material. A material with low cohesion is friable and can be easily torn into pieces. Materials such as styrofoam have little cohesion and are, therefore, unacceptable. PVC and polyethylene exhibit good cohesion.

If a material is to be used over long periods of time it must have good cohesive strength. Cell-wall strength is related to cohesive strength or its tensile quality. Materials such as polyurethane have cell walls with low tensile strength, so that when depressed and rapidly released from pressure, the cell walls rupture. Materials such as styrofoam will break in compression and, therefore, show permanent compressive set.

(6) Flammability

A buoyant material ideally should not burn when exposed to an open flame; it should not be combustible. Personnel flotation material, in the form of seats, rings, and vests can be stowed in areas where fire could easily start onboard a boat, and they should not add to the fire hazard.

One of the worst materials with respect to flammability is kapok, although few of the accident reports examined show kapok-filled jackets to have contributed to a ship fire.

Many materials can be compounded to be either self-extinguishing or slow-burning. However, some of the slow-burning materials melt and drip, and serious body burns or fires can result. This is one of the main weaknesses of polyethylene as a buoyant material.

PVC can produce toxic smoke conditions when ignited and must also be considered a potential fire hazard.

(7) Inflatable Cell Design

The analyses conducted in Sections II and III indicated that the most effective jacket-type personnel flotation device used an inflatable cell design.

Inflatable buoyant jackets have been used extensively by the U. S. military services. The design of an inflatable personnel flotation device is a relatively simple one. The basic elements are the air bladder, the gas cartridge, and the actuator which causes the cartridge to release its gas into the bladder(s). Any inflatable device suffers from a problem which does not exist for an inherently buoyant personnel flotation device; it may fail to operate or the bladder could be ruptured and fail to hold the gas. The U. S. Naval Applied Science Laboratory reported no failures due to equipment deficiency had ever been reported to them; however, the use by military personnel is different from that of the civilian public, since a regularly scheduled inspection and maintenance program is possible in the military. Therefore, a review was made of possible civilian use factors which could cause failures, and a comparison of these possible failures to known properties of inflatable-cell materials. This examination is described as follows.

An examination was made of the major factors which could cause an inflatable life preserver to fail or to operate improperly. These factors consisted of conditions which could affect the personnel flotation device while stowed and when worn. Table IV-2 lists these factors and their possible effects upon the critical elements of an inflatable personnel flotation device. In a number of cases, the factor would have no significant effect upon elements (i. e., temperature upon the gas cartridge) and therefore nothing was entered into that cell of the table. Consequently, a review

LE IV-2. Critical Elements of Inflatable Life Preservers

POTENTIAL FACTORS AFFECTING DEVICE RELIABILITY	CRITICAL ELEMENTS OF INFLATABLE LIFE PRESERVER			
	AIR BLADDER	ACTUATOR–MANUAL	ACTUATOR–AUTOMATIC	GAS CARTRIDGE
ENVIRONMENTAL/STOWAGE				
• TEMPERATURE	COULD CAUSE STIFFNESS AND CRACKING IN COLD WEATHER. COULD LOSE MATERIAL STRENGTH OR BONDING ADHESION IN HOT WEATHER.	-	-	-
• HUMIDITY/WATER SPRAY	CONTINUAL EXPOSURE TO HUMIDITY AND WATER COULD CAUSE FABRIC TO DEGRADE OR ADHESION TO BE LOST.	METALLIC PARTS COULD BECOME CORRODED	AUTOMATIC ACTUATOR ELEMENT COULD BE INADVERTENTLY ACTUATED	-
• EXPOSURE TO GAS/OILS	FABRIC AND BONDING COULD DETERIORATE AFTER PROLONGED EXPOSURE TO GAS OR OIL	POSSIBLE LOSS OF NECESSARY MOVING PART LUBRICATION	POSSIBLE AUTOMATIC ACTUATION AFTER IMMERSION	-
• PACKING PRESSURE OR LOADING	SURFACES MAY BLOCK OR ADHERE TO ONE ANOTHER. PRESSURE MAY CAUSE SHARP OBJECT TO PUNCTURE FABRIC.	-	-	-
USAGE/WEAR EFFECTS				
• ROUGH HANDLING	MATERIAL MAY BE ABRADED OR PUNCTURED	ACTUATOR MAY BE DEFORMED OR DAMAGED	ACTUATOR MAY BE DEFORMED OR DAMAGED	-
• USE IN FOUL WEATHER	-	-	ACTUATOR MAY BE INADVERTENTLY ACTUATED	-
• PRIOR USE OF LIFE PRESERVER	-	-	EXPENDED AUTOMATIC ELEMENT, MAY NOT HAVE BEEN REPLACED	EXPENDED GAS CARTRIDGE MAY NOT HAVE BEEN REPLACED

was made of U. S. Navy specifications for inflatable personnel flotation devices. In addition, discussions were held with U. S. Navy personnel concerning these listed problem areas and the degree to which current state-of-the-art resolves them. Table IV-3 shows the degree to which the possible effects of the stowage and use factors are satisfied. It can be seen from this table that the only problem area which is not fully met by current state-of-the-art is the effects of puncturing and the maintenance or resupply of spent actuators and cartridges. As previously discussed, the puncture problem can be reduced considerably by enclosing the bulk of the bladder in a puncture resistant package. It is difficult to positively ensure the replacement of expended cartridges. One possible method of reducing the chance of having a personnel flotation device without an unused gas cartridge would be to use two (or more) cartridges. This would require a trigger which would, when pulled once, puncture one cartridge. A second actuation of the trigger would puncture the second cartridge. This would result in a more complex actuator design and would not completely remove the possibility of both cartridges being used, but it would reduce this likelihood. The replacement of a spent automatic actuator element cannot be positively ensured; however, proper design can increase the likelihood of observation of its

TABLE IV-3. Critical Elements of Inflatable Life Preserver

TABLE IV-3

USAGE/WEAR EFFECTS	CRITICAL ELEMENTS OF INFLATABLE LIFE PRESERVER			
	AIR BLADDER	ACTUATOR—MANUAL	ACTUATOR—AUTOMATIC	GAS CARTRIDGE
• USE IN FOUL WEATHER	—	—	ASSEMBLY CAN BE DESIGNED SO THAT WATER SPRAY AND RAIN COULD ONLY ON RARE OCCASIONS WET THE ACTUATOR	—
• PRIOR USE OF LIFE PRESERVER	—	—	NO APPARENT TECHNIQUE TO POSITIVELY ENSURE REPLACEMENT OF SPENT ACTUATOR. USE OF FLAGGING OR DISPLAY WINDOW TO SHOW STATE OF AUTOMATIC ACTUATING MECHANISM.	NO APPARENT TECHNIQUE TO POSITIVELY ENSURE REPLACEMENT OF SPENT GAS CARTRIDGE. USE OF TWO CARTRIDGES, EACH SEPARATELY ACTUATED COULD REDUCE THE LIKELIHOOD OF A LIFE PRESERVER FAILURE DUE TO A SPENT CARTRIDGE.

state of use by the wearer. Use of flagging techniques or of a display window would help considerably.

In summary, it can be seen that the materials and equipment associated with inflatable personnel flotation devices are highly reliable; the major problem is the one of human error: failure to replace a necessary spent cartridge or automatic inflation element. This later problem can be reduced, but it is unlikely that it can be completely eliminated. This conclusion is supported by the U. S. Navy's experience in that no failures of inflatable personnel flotation devices have yet been attributed to equipment; all failures were caused by human errors.

V. COST ANALYSIS

This chapter is concerned with the development of a cost methodology for the cost/performance evaluation of personnel flotation devices.

No methodology was found that permits the cost estimate of new flotation devices--new in the sense of a new design or in the sense of a new material--unless a detailed operation-by-operation cost estimate is made. Therefore, this chapter has been prepared to present a method to serve as a basis for quick estimate of costs for new designs.

1. THE COST BACKGROUND

Personnel flotation devices being marketed today fall into two general categories:

- U. S. Coast Guard approved
- U. S. Coast Guard not approved.

In the development of the cost methodology, we only consider personnel flotation devices approved by the U. S. Coast Guard, since they are built to known standards.

The market for personnel flotation devices is very competitive, as can be seen in Table V-1. The analysis of the manufacturers' suggested retail prices presented indicates that, except for a few cases, there are no major differences in price for any one item. The differences in price that do exist may be due to local conditions such as labor cost, transportation cost, taxes, etc.

Therefore, if we assume that a new flotation device is a modification of a current model, either by the use of a new material or by modifying the design, the average of the suggested retail prices of the current model can be used as the base price for estimating the cost of the new device to the user.

2. COST STRUCTURE

The definition of the cost structure is necessary to find the effect of the two primary components of the production cost in the retail price of a new device. This structure is as follows:

- Production cost
  - Material
  - Labor
- Overhead cost

TABLE V-1. Representative Suggested Retail Prices of Personnel Flotation Devices (Dollars)

MANUFACTURER	PFD MODEL					
	160,047	160,052 (62)	160,052 (TYPE II)	160,002	160,055	160,048
A	4.70	7.80	11.10	11.70	17.15	
B	4.75	–	–	–	–	
C	–	–	10.95	–	–	
D	–	–	10.95	–	19.95	
E	5.50	6.25	–	–	–	
F	4.75	–	–	12.00	17.00	
G	3.18	–	–	8.48	–	
H	–	–	13.95	–	– –	
I	2.95	–	–	–	–	
J	4.75	8.90	–	12.60	17.10	5.50
K	5.00	8.73	–	13.98	–	5.15
L	–	9.00	–	13.50	17.50	5.95
M	–	–	–	12.50	14.25	5.25
AVERAGE COST	4.45	8.14	11.74	12.11	17.16	5.46

- Manufacturer's profit
- Salesman's commission
- Jobber's markup
- Dealer's markup.

The analysis of the data on hand and known business practices indicates that the cost breakdown, as a percentage of the retail price, can be assumed with a good degree of accuracy as indicated in Table V-2. Items 2 through 6 of cost in Table V-2 can, for the purposes of this study, be estimated to be constant, leaving as the only variable for the cost estimate item 1 (production labor and materials).

TABLE V-2. Cost Breakdowns as a Percentage of the Retail Price

COST ITEM	PERCENT OF RETAIL PRICE
(1) PRODUCTION (MATERIAL AND LABOR)	26
(2) OVERHEAD	13
(3) MANUFACTURER'S PROFIT	4
TOTAL MANUFACTURING	43
(4) SALESMAN	2
(5) DISTRIBUTOR	5
(6) DEALER	50
TOTAL DISTRIBUTION AND SALES	57
TOTAL RETAIL	100

3. THE COST METHODOLOGY FOR NEW FLOTATION DEVICES

The cost methodology presented in this section is based on the fact that a new flotation device can be assumed to be a modification of an existing model (base model) either because a new material is used or because the design is changed or both. The steps for estimating the cost of the new device are as follows:

(1) Choose similar current device

(2) Find average cost from as many manufacturers as possible

(3) Determine production cost using cost breakdown presented in the previous section

(4) Estimate material cost

(5) Determine labor cost by subtracting (4) from (3)

(6) Estimate variations in material cost

(7) Estimate variations in labor cost

(8) Add (6) and (7)

(9) Determine retail price of new device on the basis of the percentages shown in the cost breakdown in the previous section.

This cost methodology does not consider the increase in price due to the amortization of the research, development, test, and evaluation costs; it only provides a quick way for estimating retail prices based on changes in production cost.

4. RESEARCH, DEVELOPMENT, TEST, AND EVALUATION COST

These are the costs incurred in the development of a new device and include the following items:

- Test and analysis of existing flotation devices
- Research analysis for definition of improved flotation devices
- Development and test and evaluation of new materials
- Design and production of prototype flotation devices
- Test and evaluation of new flotation devices
- Management of the program (government).

There are three ways that the RDT&E cost can be amortized:

(1) The U. S. Government (U. S. Coast Guard) pays for the RDT&E costs and writes a manufacturing specification with no cost to the manufacturer and the user.

(2) An independent laboratory develops the manufacturing specifications to meet the U. S. Coast Guard performance specifications, and charges a royalty to the manufacturer.

(3) A manufacturer develops the new flotation device to meet the U. S. Coast Guard specifications and allocates this cost to the product on the basis of the probable number of personnel flotation devices whose sales can be forecast.

Most of the development of new flotation devices until now has been conducted by the manufacturer without U. S. C. G. financial assistance. These development efforts have not involved large expenditures of money and, therefore, the PFD's produced were marketed at prices attractive to the user. If much larger scale research and development is undertaken by manufacturers the cost of the PFD's will increase, depending on the number of production units, to a cost not attractive to the user, as shown in Figure V-1.

To maintain the price of new flotation devices at a level attractive to the user it is considered that the development of new devices could be a combined government-industry effort, with government providing management guidance and funds for research, test, and evaluation, and industry producing the prototypes for government test.

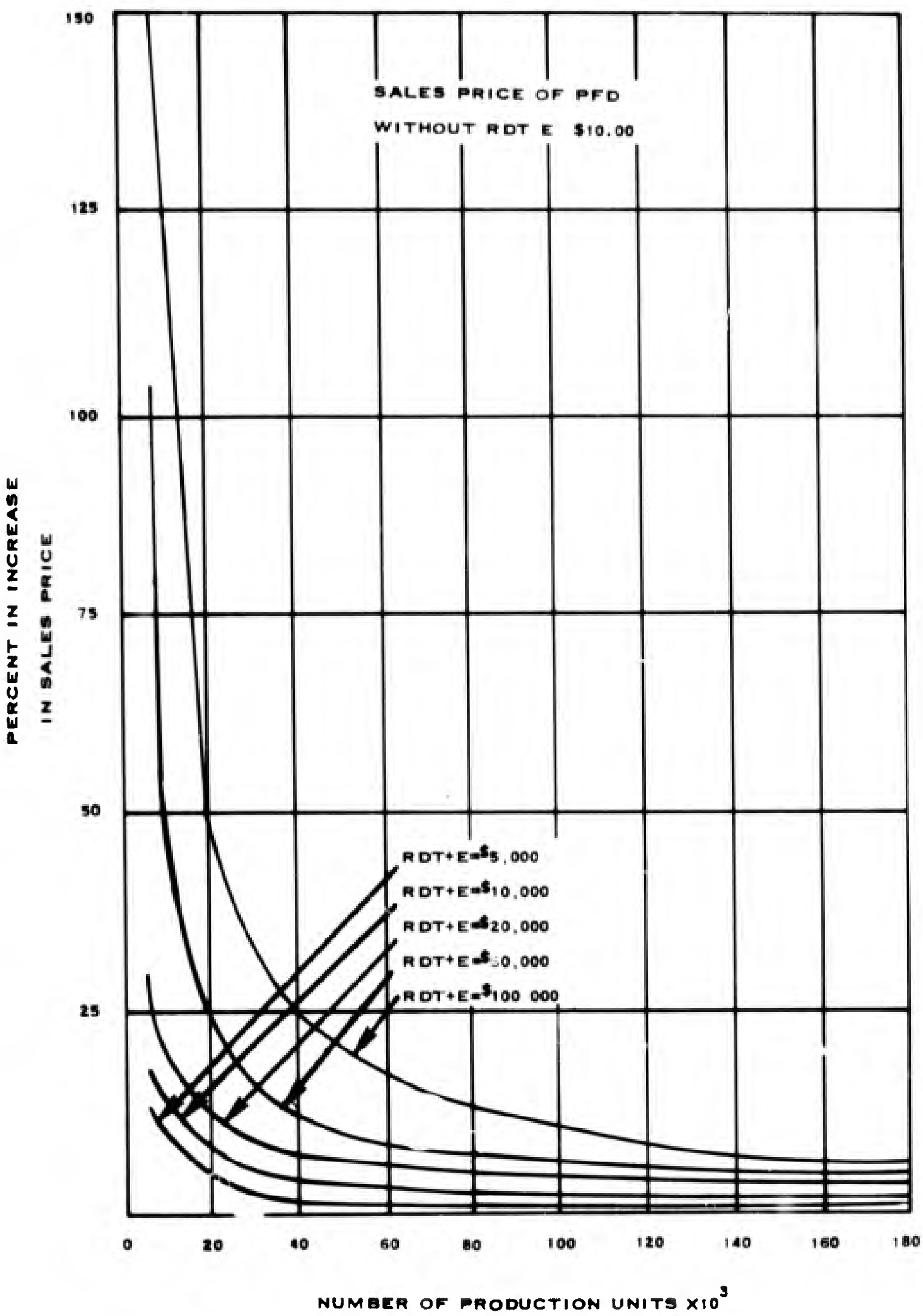


FIGURE V-1. Percent Increase in Sales Price Versus Number of Production Units to Amortize RDT&E Costs

VI. RECOMMENDATIONS

As a result of this study and activities associated with this study, a number of recommended actions are suggested. The recommendations suggested can be divided into what is believed to be necessary actions which can be performed in the immediate future and those actions which cannot be fully implemented until the first recommended actions have been completed. These actions can be divided into Phase I, immediate actions, and Phase II, follow-on activity. The following summarizes the objectives of each phase:

1. PHASE I

Tests should be conducted to verify and augment the analyses of the personnel flotation requirements. These tests should better define the buoyancy requirements in still and moving water, the attitude-achieving capabilities and effects of different PFD configurations for different men and women, and the turning moment requirements.

The personnel flotation device requirements study should be expanded through a limited effort to define the antiexposure and search and rescue aides requirements and capabilities required for personnel flotation devices.

Field tests should be made of kapok and various inflatable jacket-type personnel flotation devices to assess their acceptability under use and stowage conditions typical of the pleasure boat and vessel-for-hire operations.

A study should be performed to determine the boating habits of the pleasure boating public as well as to define the characteristics of a personnel flotation device which affects its wear acceptance. The objectives of this study would be to determine how important wearing a jacket-type personnel flotation device is to water safety and secondly to determine what must be done to develop a wearable, effective personnel flotation device.

2. PHASE II

The results of this study, together with the results of Phase I, should be used for guidance in future actions related to improving personnel flotation devices and water safety. The areas of action which probably should be performed are as follows:

(1) Modification of Existing PFD Specifications

Conditional to the results obtained, the current USCG specifications should approve noninherently buoyant materials. The specifications should be modified to eliminate buoyant materials located on the back of a jacket used on vessels for hire. Further, the specification for buoyancy and straps should be modified.

(2) Improved Accident Reporting

Accident reporting should be made uniform, consistent, and centrally maintained. The intent of the reporting should be to provide information necessary to enhance water safety rather than to define liability.

(3) Water Safety Information Program

An information and publicity program should be initiated using existing, available, cooperative agencies such as TV programs and TV advertising agencies, the Ford Foundation, and periodicals. The intent of this program is to gain popular acceptance of the value of PFD and water safety.

3. PHASE I TESTS AND STUDIES

The Phase I test activities recommended can be further defined in terms of their objectives and a suggested plan for their achievement. The following objectives are recommended for testing:

(1) Still Water Tests

Tests should be administered to a sufficiently large number of men, women, and children to determine the buoyancy required to support them in still water for various freeboards. Additional tests should be made to determine the effects of swimming exertion and clothing upon buoyancy.

The bulk of the tests should be conducted at a USCG station using USCG personnel both to administer and to perform as subjects. Physical data on height and weight should be obtained; specific gravity should be measured by determining body volume. These tests should first determine the buoyancy required for various freeboards under normal breathing conditions and wearing swimming trunks only. During the same test session, the person should be rotated through various body angles, with and without a PFD. The turning moment required to maintain the person in each of the specified angles should be measured for both conditions. Finally, for a limited percentage of the subjects, the turning moment required to turn a person as well as the time to turn for various turning moments should be established.

The results of these tests should be used to define the following:

- Buoyancy requirements as a function of freeboard
- Buoyancy requirements as a function of directly measurable physical characteristics--i. e., weight, height, etc.
- Buoyancy requirements as a function of sex
- Turning moment required to maintain a floating person in various angles
- Turning moment required to maintain a floating person wearing a buoyant vest in various angles
- Time to turn to a stable attitude as a function of turning moment.

These results can be used to further resolve and verify the original assumptions as follows:

- The difference between turning moment required to maintain a person with and without a PFD defines the in-place turning moment of a PFD
- The use of different types of PFD in the tests permits an identification of the effects of thickness, length, and geometry
- The use of PFD's with and without straps permits an identification of the effects of straps
- Comparison of the test-derived results to the analytically derived data validates or defines the modifications required of the analytic model to make it conform to the test data points.

(2) Moving Water Tests

Tests should be administered to a more limited number of men and women to determine the effects of waves upon buoyancy, body orientation, and turning moment. The average height and period should be measured together with the variation in head freeboard. This should be done without PFD and with PFD which provide different buoyancies and turning moment characteristics.

These tests should be conducted by USCG personnel using USCG personnel as subjects. If possible, a sample of the subjects originally used on the still water tests should be used on these tests. The results of these tests should be used to define the following:

- Freeboard to mouth as a function of time, wave, height, and period (no PFD)
- Effects of PFD buoyancy upon freeboard and freeboard time variation
- Effects of PFD turning moment and turning moment rate upon body orientation and freeboard.

These results can be used to further resolve and verify or modify the results and conclusions reached in the still water tests.

(3) Kapok Tests

Kapok appears to have marginal safety characteristics since limited data indicate a rapid loss of buoyancy can occur when the material is agitated. Test should therefore be conducted in which people wearing kapok-filled jackets, whose containing bags have ruptures of varying sizes, swim and/or struggle in a fashion similar to a person who has entered the water due to an accident. The results of these tests can provide the following data:

- Buoyancy loss as a function of swimming/struggle duration and rupture size
- Buoyancy loss as a function of kapok quality.

(4) Inflatable Cell Tests

Inflatable PFD jackets of different designs and using different quality cell materials should be stowed in various conditions aboard both USCG and cooperating civilian boats. The stowage conditions should represent nominal and poor stowage environments. In addition, USCG and/or cooperating civilian personnel should wear these devices while performing routine activities about ship. The jackets should be collected after the test period and subjected to detailed inspection and tests. If possible, existing Navy or Air Force agencies should perform the inspection and tests.

(5) Personnel Flotation Device Wear Study

This study would consist of two interrelated substudies. The first substudy would examine the habits of the pleasure-boating population concerning whether and under what conditions they wear personnel flotation devices (PFD), what types of PFD's are kept on board the boat, and where these devices are stowed. In addition, this substudy would survey available accident reports to determine from these reports the effects of the availability, or lack of availability, of PFD's upon rescue and survival of people in the accidents. The intent of this substudy is to develop sufficient information to determine the availability of personnel flotation devices and the implications of the lack of availability or non-wearing of jacket-type PFD's upon water safety. The second substudy would gather data and analyze the factors which affect the wear acceptance of personnel flotation devices. This activity would consist of both a questionnaire survey plus in-depth interviews with members of the pleasure-boating public to develop reliable, creditable information on the factors which influence the wear acceptance of PFD's.

- Assess the importance of wearing jacket-type PFD's
- Estimate the effects of different stowage locations and methods upon the usefulness of PFD's
- Develop information of wear-acceptance factors and provide data necessary to develop acceptable and safe PFD's
- Provide sufficient creditable data on accidents and wear-acceptance factors to perform a cost/effectiveness determination of various forms of PFD's
- Provide information necessary to determine the relative importance of subsequent Phase II activities.

The accident and wear habits portion of this study should consist of the following tasks:

Task 1 Accident Records Investigation

An investigation would be made of all pleasure vessel accident records available within the U. S. Coast Guard together with meetings with U. S. C. G. and other groups concerned with water safety. Water accidents occurring during the period of this study would be studied in depth. The information gathered would define the factors contributing to the accident, the details of the accident with emphasis on those aspects involving PFD's availability and use, and the nature of any rescue operations.

Task 2 On-Site Interviews

Survey personnel would accompany U. S. Coast Guard personnel while they performed pleasure craft inspections. The accompanying personnel would, when given permission, interview the persons aboard the boat concerning the reasons why they were or were not wearing PFD's. In addition, data on the number, type, trade name, and location of all PFD's aboard the boat would be obtained.

Task 3 Wear Tests

A number of pleasure-boat users would be contacted to determine their reactions to various types of jacket-type PFD's.

Task 4 Questionnaire Survey

A questionnaire would be developed for mailing to pleasure-boat owners. The questionnaire would be used to gather a volume of data on the boating habits, i.e., frequency and duration of boating, passengers, as well as information on personnel flotation device wear habits.

Task 5 Wear Data Synthesis

The wear data obtained from Tasks 2, 3, and 4 would be analyzed to ensure that no biases were obtained in the data and that the results are comparable.

Task 6 Data Analysis and Evaluation

The data developed in Tasks 1 and 5 would be used to analyze the significance of wearing PFD's and/or their availability with respect to water safety and also to define the relationships between PFD's characteristics and their wear acceptance.

4. PHASE I SCHEDULE AND MANPOWER REQUIREMENTS

The schedules shown in Figure VI-1 and VI-2 grossly define the probable times required for activity. It is estimated that a minimum of six persons are required for one year to perform the studies recommended for Phase I. At least one of these persons and preferably two should be U. S. Coast Guard personnel.

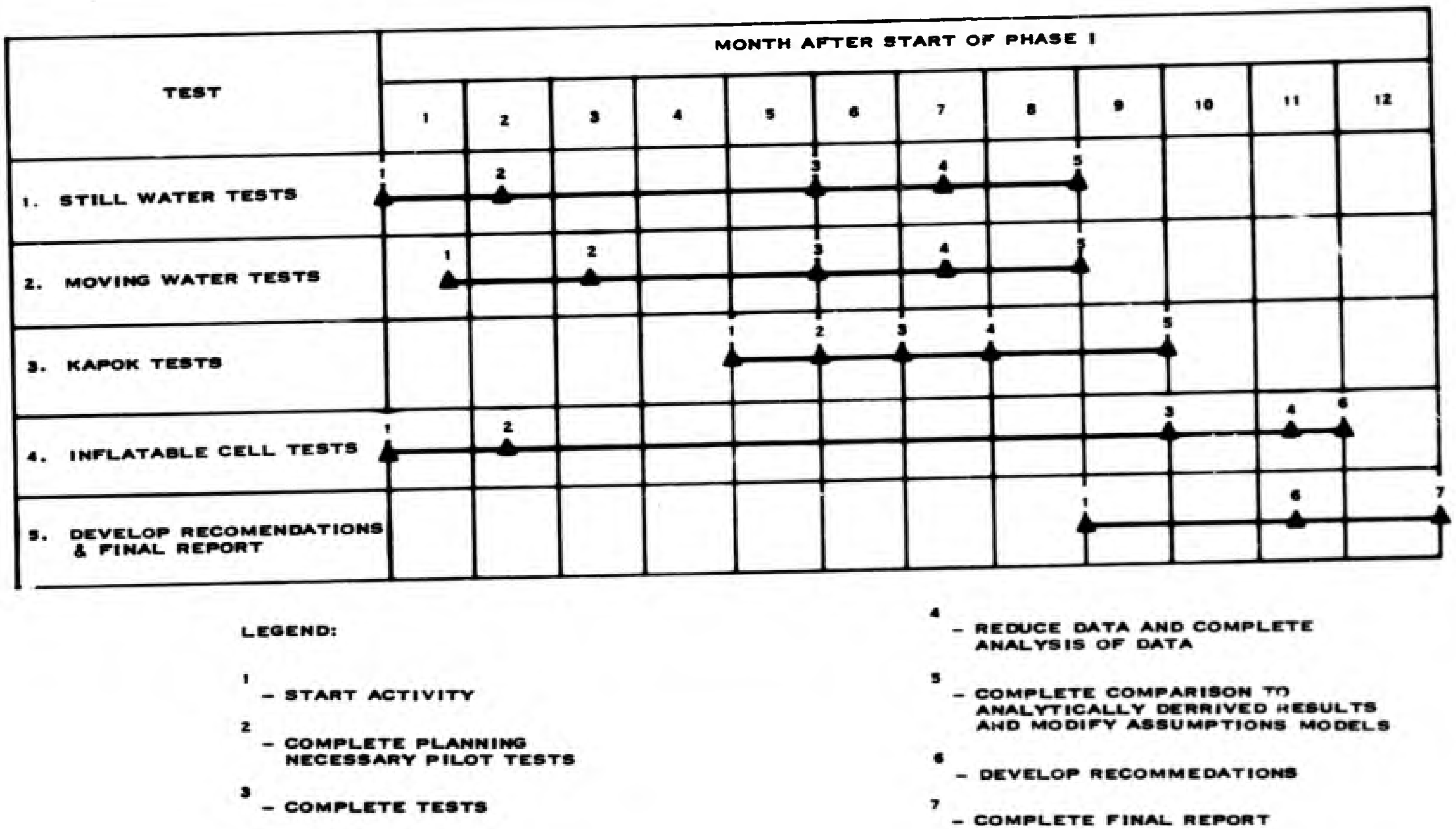


FIGURE VI-1. Schedule for Tests and Test Activities

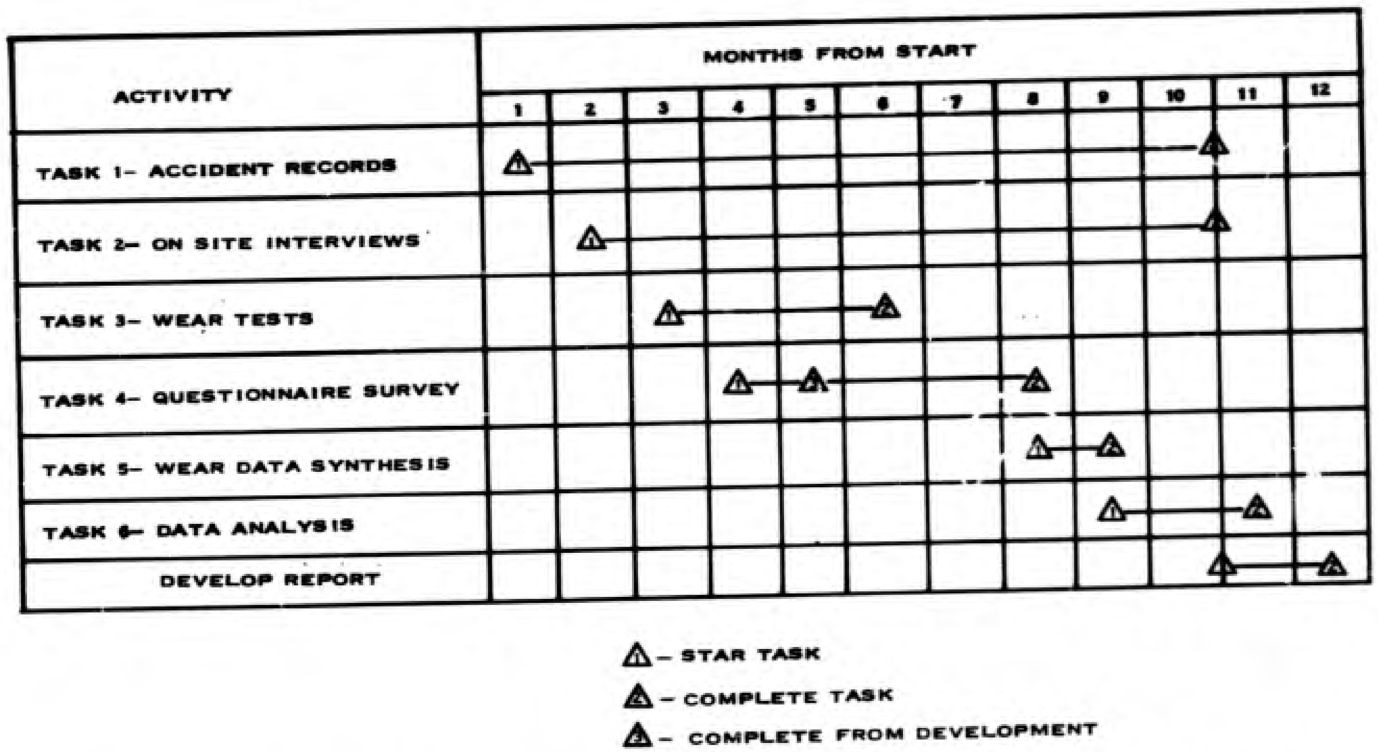


FIGURE VI-2 Schedule For Personnel Flotation Device Wear Study

(1) Modification of Existing PFD Specifications, Acceptance, and Inspection Procedures

If the results obtained in the completed analytic study are supported by the Phase I results, modifications to current U. S. Coast Guard specifications for inherently buoyant vests should be made. It is not envisioned that this will take an extensive effort. However, if the results of the Phase I study show that inflatable cell vests should be approved by the U. S. Coast Guard, extensive effort will be required to define the specifications. It is recommended, in this case, that U. S. Navy specifications for materials, and configurations for initial acceptance, manufacture and product acceptance be used as a point of departure. Personnel flotation devices can be manufactured at reasonably low costs, i.e., about $12.00 while still being of MIL specification quality. Therefore, it would appear reasonable to retain U. S. Navy specifications. If the number of approved manufacturers were kept to a limited group, U. S. Navy quality control inspection procedures could and should be maintained.

(2) Water Safety Information System

It is recommended that the present water safety information system be expanded from the accident records system to an information system which will permit a better assessment of the problems, casual factors, and determination of corrective actions.

An information system which can provide this capability would require a considerable elaboration upon the existing accident reporting, storage, and data disseminating methods currently used. In general, the system must have uniform information collection, central data storage, and fairly elaborate data retrieval methods. The most difficult part of any system of this type is to determine what information is necessary and the feasibility of collecting this information. A second major difficulty is gaining concurrence on the information collection practices by all the agencies involved in water safety.

It is, therefore, recommended that a series of meetings be held to initiate this system. The meetings should first define the information believed necessary to decision-making in water safety. An ad hoc group should be formed to explore the means of expanding existing accident and other reporting/logging records to satisfy these information needs. Existing legal, organizational, and procedural constraints as well as the practical problems in gathering the information should be considered. Additional meetings must be held to gain concurrence by other involved federal, state, and local organizations, on the recommendations of the working group. At this time a detailed information system can be proposed which would define the records necessary, the routing, data extraction, collation, and presentation methods. In addition, this definition should also specify the incremental steps by which this system could be developed and the costs necessary to develop and maintain it.

Water safety, and in particular, accident prevention, covers a very large number of areas. It is suggested, at this time, that any information system for water safety be expanded about the present nucleus of data records and, in detail, from the personnel flotation device problem area. The information gathered in the Phase I activities should provide a solid base for the start of the information system. The information gathered on the boating habits and the accidents should provide an excellent framework from which an on-going information system can develop.

(3) Water Safety Public Information Program

A concerted information program directed to the boating public could be one of the most effective safety programs proposed. A concerted program could be developed by the U. S. Coast Guard in cooperation with insurance corporations and foundations, such as the Ford Foundation. If properly implemented, costs should be minimal. Magazines, such as the consumer advisory type, should welcome information for articles on PFD, boats, etc.

Similarly, the TV media should find the area of water safety an extremely attractive one for programming.

The public can be influenced and recreational boating is a popular subject. There is at present virtually no effective information programming reaching the public. Subsequent to the Phase I studies, in which the problems and needs are better defined, meetings should be held with organizations which have an interest in water safety and could contribute to financing a public information program. Similarly, meetings should be held with TV programming personnel, advertising groups and magazine publishers to develop programs and articles to educate and influence the boating public.

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APPENDIX

The Appendix contains material required to define assumptions and analytic relationships used in this study. Further, it contains amplification and/or supporting documentation related to certain statements made in this study. The supporting material is organized to correspond to the sections of the main report.

1. REVIEW OF SURVIVAL AND ACCIDENT INVESTIGATION LITERATURE

Fatalities in water and water accident data are rather difficult to deal with for several reasons. Fatalities associated with water accidents may occur for multiple reasons. Moreover, documentation about such cases frequently is flimsy, lacking in detail and verification. Very often, there is reliance only on a survivor's or observer's memory. Water accident investigation is usually incomplete, partly because of circumstances--examination is difficult--and partly for the reason that the body is not immediately recovered, occasionally never. Even when the body is recovered, it is infrequent that a medical autopsy is performed to ascertain exact cause of death. If an autopsy is not done, it is usually impossible to differentiate drowning from exposure cases. In many areas, only lay coroners are employed, and modern medical examination techniques are not used either to supplant or supplement them.

The difficulty of accident investigation is compounded by lack of data--bodies and craft may drift or be washed from accident sites; no skid marks (and often no other evidence) are left as in an automobile accident. Frequently, there are no observers and the victim's body and craft may reveal few clues to the exact happenings and order of events. For reasons such as these, it is well to look at water accident and survival data with caution and reservation.

The data reviewed were from a variety of sources--U.S. military, U.S. Coast Guard, foreign military, records of sea and aircraft crashes or ditchings into the sea. The data pertained to several different considerations such as:

- Personnel flotation devices and crew lifecraft
- Exposure
- Water and food.

2. STATISTICS ON SURVIVAL AT SEA

From several different sources, certain considerations appear to be critical to survival.

(1) Personal Flotation Devices and Crew Lifecraft

Chances aboard a lifeboat or liferaft are reasonably good[11], whereas chances in the water generally appear poor; 26 percent (approximately 7,000 from a total of 27,000 persons initially aboard merchant ships) were lost before reaching a lifeboat, another 6 percent (approximately 1,600) expired after reaching lifecraft; 68 percent in all (approximately 18,350) were rescued.

Few instances are recorded of survivors being in the water, with or without flotation devices, for more than 12 hours and very few cases of over 24 hours[11].

(2) Exposure

Exposure (some combination of wind, sun, spray and/or cold) is a serious threat[10, 11] to survival; "cold was a most important cause of death before and after boarding the lifecraft..."; the death rate was 20 to 30 percent on short voyages at temperatures below 5°C (41°F) but less than 1 percent on short voyages at temperatures over 20°C (68°F).

(3) Water and Food

Insufficient food and water, as well as exposure, probably contributed to fatalities on longer voyages aboard lifecraft[11]. "There was a high mortality on long voyages. Only 2 percent of the men who reached lifecraft were lost if they were picked up by the second day, but 26 percent died when they were adrift for more than 15 days; water was the primary requirement of the survivors; food was of secondary importance except in cold climates."

(4) Personnel Flotation Devices--Requirements

A number of theoretical and empirical studies have been done to determine or assess requirements for personnel flotation devices. A brief review of some foreign studies is illuminating.

A British research team had much to say about the requirements for a personnel flotation device; unfortunately, the report was only a small representation of their apparently thorough consideration of this topic[8]; they argued in general that:

- "Buoyancy must not be so symmetrically distributed that several positions of stability become possible by small changes of posture of the subject within the harness.
- The possibility of shift of position of maximum buoyancy...must be either eliminated or allowed for.
- The harness which attaches the jacket to the subject must maintain in all conditions, a satisfactory relationship between them."

Another foreign study indicated the following flotation device requirements (12, paraphrase of comments):

- Provide sufficient buoyancy to keep head and breathing openings safely above water
- Provide turning moment which will automatically bring the body quickly into a stable, oblique, supine position and maintain this position independent of body condition, clothing, and water conditions
- Not interfere with personal movements--swimming or other
- Provide buoyancy unaffected by oil or petrol
- Possess strong wear resistance under heavy conditions
- Resist any deterioration of structure or performance under storage conditions
- Have acceptable user characteristics with regard to:
  - softness
  - comfort
  - weight

- Possess donning characteristics which permit simple, unaided donning under the most difficult conditions, even in the dark
- Wearing the device must not impair senses or breathing
- Device should have search-and-rescue aids
  - Color, reflectors
  - Other acoustic or optic means of communication
- Device should be designed and composed so as to minimize injury to user when jumping into water from a great height
- Device should fit a wide variety of body sizes and shapes

From injury and fatality reports a number of requirements were gleaned (11):

- Incapacitated persons became drowning victims because their lifejackets had no means of preventing their heads from falling forward into the water
- In a nearly horizontal float position, the device-user's tongue may fall into the back of the throat and cause choking.

(5) Other Survival Factors

Other factors to consider were indicated in another study (6): persons in peril for an extended period of time were unable to assist in their own retrieval because cold numbed them into near incapacitation. This suggests the floatation devices and coordinate search-and-rescue craft gear must be designed so as to facilitate retrieval even when the survivor is unable to assist in the operation.

Time in water is a critical factor--in terms of individual threat from exposure, stress, fatigue, etc. Visual and auditory devices and signals to reduce search-and-rescue time are critical (6). Premeditated abandoning ship with preparatory radio distress calls usually proved the most effective in terms of survival. The research on electronic beacons, dyes, smoke, hand-held flares, and other signalling devices should be pursued. Poor reliability seems to mar many potentially valuable search-and-rescue aids.

A review of data recorded for military aircraft accidents, including survival considerations, reiterating some of the factors already mentioned, has some relevance to the concern of our present study (10), it was found that:

- Availability of appropriate survival equipment is critical
- Availability of signalling devices is particularly important (e.g., mirrors, flares, sea markers, dyes, and/or flashlights)
- Radio signals transmitted prior to egression are much more effective than those after the accident (e.g., high failure rate with emergency radio equipment)
- There is a great need for water survival training (few survive without adequate knowledge or equipment)
- There is a serious requirement for pilots to personally double check the condition of their personal survival equipment
- Some degree of cold and exposure was experienced by over 40 percent of all personnel who egressed over water.

A series of studies by the Naval Medical Research staff (3, 5 and 12) indicates that some advances have been made in the area of survival wear. The research staff have determined that some form of thermal protection is needed for prolonged immersion in water at temperatures of 75°F and below. Temperatures of ocean areas are typically below 75°F, particularly in the Atlantic Ocean, and most inland waterways are below the 75°F level much of the year. The research in survival wear is still very much in process; heat generating systems are being explored in conjunction with them. The study of survival suits in conjunction with flotation devices has come under investigation by the Coast Guard as reported in a May 1968 report issued by Baltimore Field Test and Development Center.

The remaining discussion centers on recreational and commercial craft accident statistics.

3. RECREATIONAL AND COMMERCIAL CRAFT ACCIDENT STATISTICS IN THE UNITED STATES

The first matter considered was that concerning the trends in fatalities, drownings, and injuries, comparing recreational and commercial craft. Reviewing Figure A-1, we see that drownings, and to a lesser extent, fatalities involving personnel associated with commercial craft have been at a relatively stable level during the period 1962-1966. For recreational boating over the same time period, however, drownings and fatalities generally have risen. Injuries among recreational boaters reached a prominent peak in

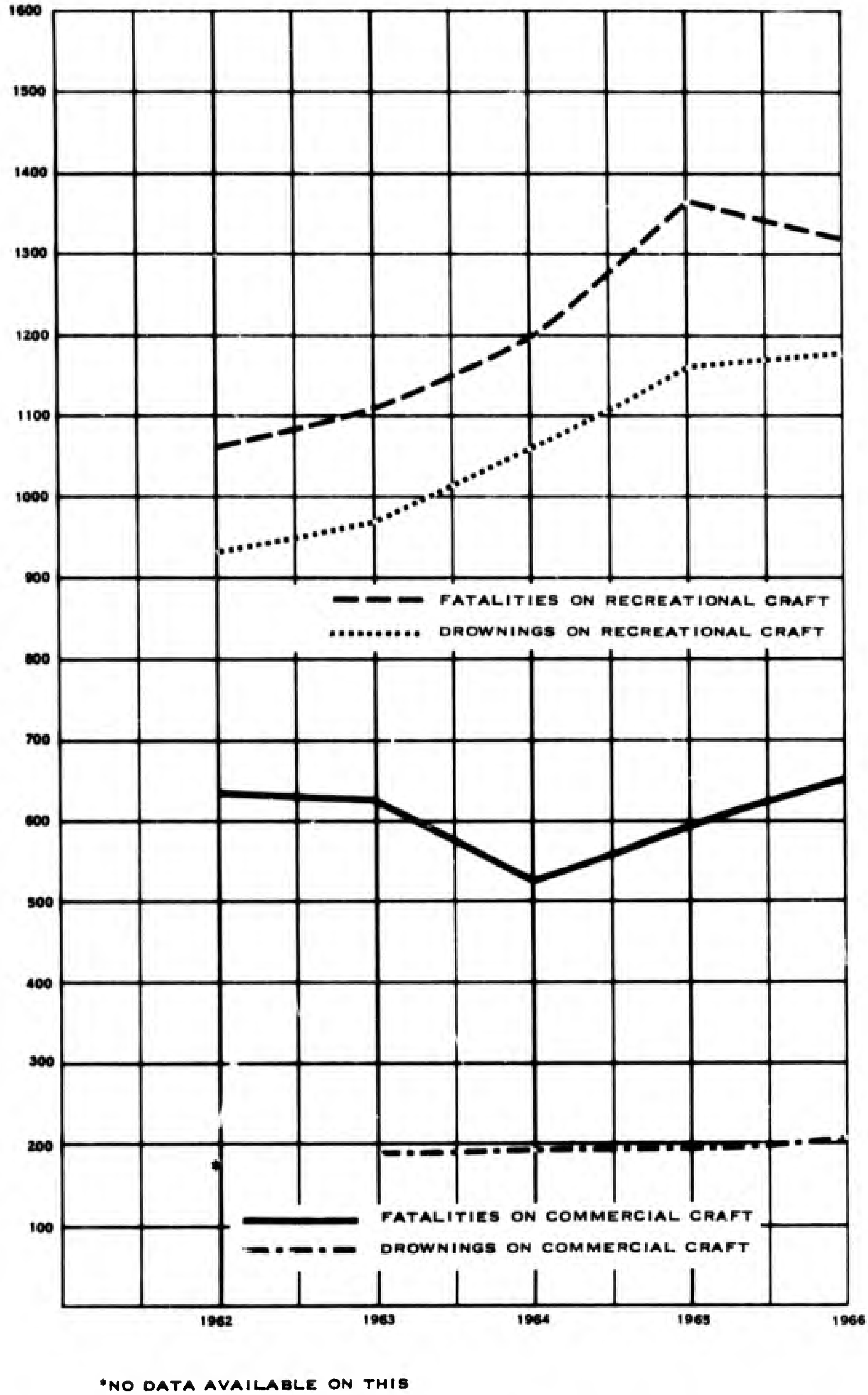


FIGURE A-1. Fatalities and Drownings, by Commercial and Recreational Craft

1966; no comparably large increase was to be found for injuries among commercial craft personnel. See Figure A-2.

From all fatalities occurring in 1966, two-thirds involved recreational boaters; only one-third were associated with commercial craft activity. Even more marked are the figures for drownings where 85% took place with recreational craft. Only for injuries is a higher proportion registered for commercial rather than recreational craft, 58 versus 42 percent, see Table A-1.

In the context of this study, it would appear on the basis of the absolute drowning rate* that a heavy concentration of analysis on flotation device requirements for recreational craft is merited. The emphasis on analysis of pleasure craft flotation device requirements and use becomes even more critical in that over 85 percent (315 from a total of 367 cases) of fatalities aboard recreational craft not involving a craft accident had to do with falling overboard.

* The relative drowning rate may be a more appropriate figure, unfortunately, it is not used frequently enough, although some attempt at such a measure was made in the 1965 annual recreation boating report - death rate per 10,000 boats. The relative rate is a measure of frequency of occurrence (of drowning or fatalities in this case) to total opportunities. A more satisfactory relative measure than death rate per 10,000 boats might be structured based on the total number of occasions of activity, for example the Bureau of Outdoor Recreation (Department of Interior) estimated that there were 222 million boating occasions in the summer of 1965, based on their 1965 Recreation Survey, with data collected by the Bureau of Census.

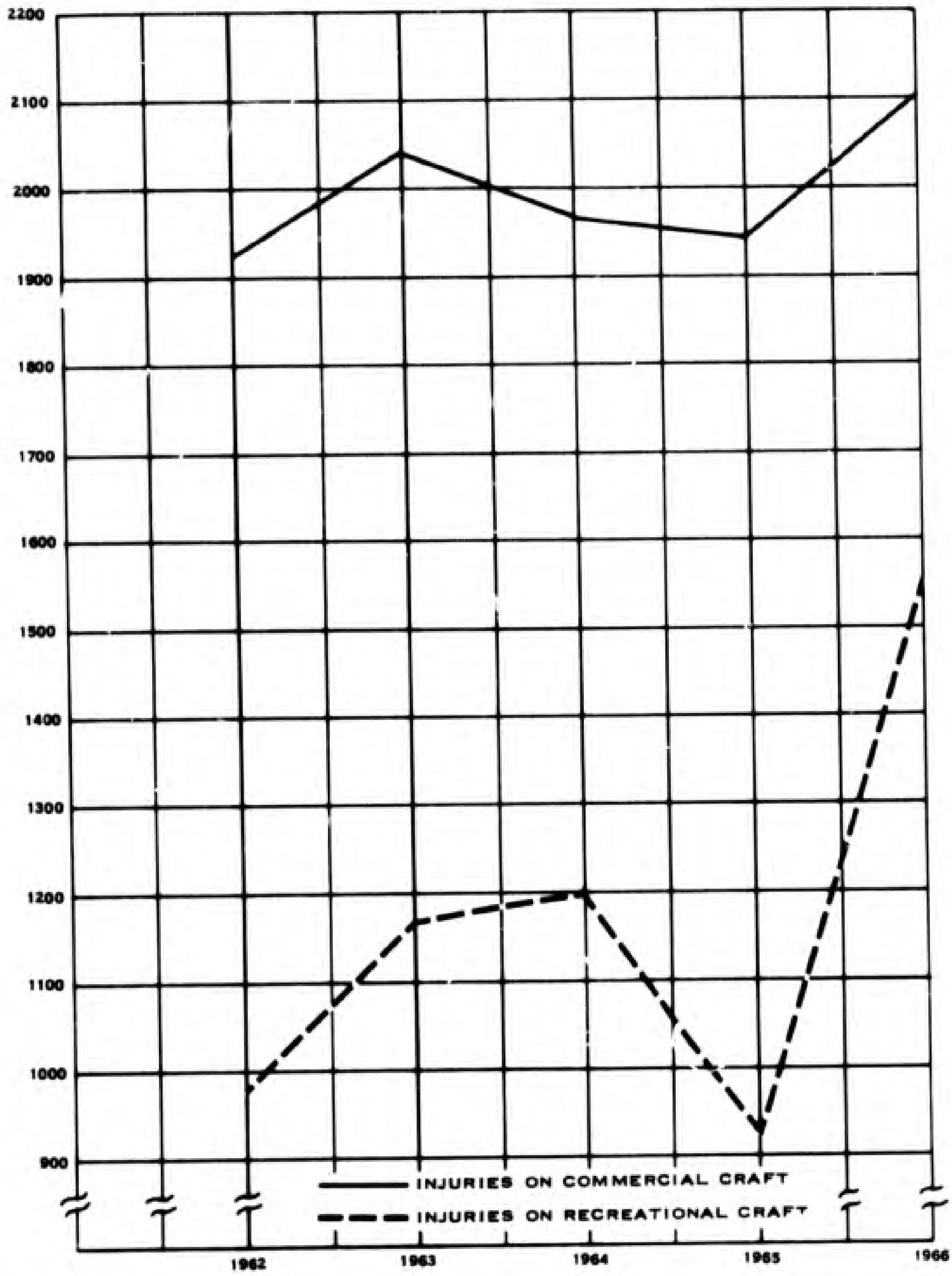


FIGURE A-2. Injuries, Commercial and Recreational Craft

TABLE A-1. Proportion of Fatalities, Drownings, and Injuries by Type of Craft--Commercial or Recreational

Type of Craft	Number of Fatalities			Number of Injuries
	Total	Drownings	Other	
Total	1,969	1,376	593	3,661
Commercial Craft	651	204	447	2,106
Recreational Craft	1,318	1,172	146	1,555

Type of Craft	Percent of Total Fatalities			Percent of Total Injuries
	Total	Drownings	Other	
Commercial Craft	33	15	75	58
Recreational Craft	67	85	25	42

Eighty percent (763 from a total of 951 cases) of all recreational boating fatalities involving a craft accident were concerned with capsizing, flooding, or sinking of one or more craft. The comparable figures for commercial craft were 25 percent (120 from a total of 473) and 29 percent (47 from a total of 178) respectively, see Tables A-2 and A-3.

In summary then, the statistical picture is such that the trends in fatalities, drownings, and injuries clearly indicate that recreational boating must be the focus of attention in terms of absolute rates. In addition, it is clear from the recent national recreation survey sponsored by the Bureau of Outdoor Recreation (Department of Interior) that the number of people and the frequency of participation in boating (as well as other water activities) is undoubtedly on the rise. Predictions for 1980 and the year 2000 anticipate increases of 76% (387 million occurrences) and 215% (694 million times) from 1965 figures; these projections are based on associated increases in expendable income, leisure time, and continuity in activity choices (no radically new activities arising). For these two reasons then, (one, the apparent current increase in actual recreational boating fatalities, drownings, and injuries, and two, the large expected increases in recreational boating activity) flotation requirements for recreational boating are an area of considerable focus in our activity of determining performance criteria.

TABLE A-2. Totals and Proportions of Fatalities and Injuries by Nature of Craft Accident and by Type of Craft

Nature of Craft Accident	Recreational Craft				Commercial Craft			
	Fatal-ities	Per-cent	In-juries	Per-cent	Fatal-ities	Per-cent	In-juries	Per-cent
Total	951	100	1,214	100	178	100	118	100
Collision	107	11	690	57	49	28	44	37
Fire or Explosion	25	3	319	26	37	21	28	24
Grounding	19	2	84	7	--	--	6	5
Capsizing, Flooding, Sinking	763	80	100	8	47	26	6	5
Heavy Weather	--	--	--	--	--	--	3	3
Other	37	4	21	2	45	25	31	26

TABLE A-3. Totals and Proportions of Fatalities and Injuries by Nature of Casualty (Not Involving Crash Accident) by Type of Craft--Commercial or Recreational

Nature of Casualty (Not Involving Craft Accident)	Recreational Craft				Commercial Craft			
	Fatal-ities	Per-cent	In-juries	Per-cent	Fatal-ities	Per-cent	In-juries	Per-cent
Total	367	100	341	100	473	100	1,988	100
Natural Causes	--	--	--	--	225	48	--	--
Fell Overboard	315	86	39	11	120	25	15	1
Disappearance	4	1	--	--	5	1	--	--
Fell Within Craft	2	1	24	7	41	9	810	41
Burns or Scalds	--	--	1	--	4	1	94	5
Struck by Boat or Propellor	21	6	168	49	--	--	--	--
Crushing or Pinching	--	--	5	2	4	1	95	5
Struck by Object	--	--	--	--	26	6	296	15
Homocide-Suicide	--	--	--	--	24	5	--	--
Overexertion, Strains, Sprains	--	--	--	--	--	--	165	8
Altercations and Misconduct	--	--	--	--	1	--	105	5
Other and Unknown	25	7	104	31	23	5	408	21

This is not to say, however, that we neglected commercial craft flotation device requirements. A large percentage of commercial craft fatalities involve the working forces--60 percent are crewmen and an additional 5 percent are longshoremen or harbor workers. Seventy-four percent of all fatalities and 83 percent of all injuries tend to occur on freighters or tankers among inspected craft. On uninspected craft, accidents in work craft (fishing boats and tugs) prevailed, with the fatality and injury rates being 55 and 58 percent respectively.

4. PERSONNEL FLOTATION DEVICES - STATISTICAL SUMMARY

Personnel flotation devices appear to be a more prevalent factor contributing to drownings occurring in recreational boating than among commercial craft. In over 25 percent of the recreational craft drowning cases (321 from 1172) occurring in 1966, the flotation device was reported to be inadequate (162), or those available were not used (169). In many additional cases, use of adequate personnel flotation devices might have meant survival, e.g., where the contributing causes were heavy clothing, intoxication, fatigue, panic, lack of swimming ability, injury before drowning, and others. For commercial vessels, in only 2 cases (from 473 in fiscal year 1967) was it documented that life preservers were inadequate, although inadequacy was reported for 34 of the injury cases (from a total of 1988); in any event each figure represents less than 2 percent of the total cases.

Looking more closely at flotation devices aboard recreational craft, summarizing over the years 1962-1965 (the time period for which comparable data were available), in those cases reported in which people were in peril to the extent that at least one fatality occurred, only 18 percent of the persons wore flotation devices. For the cases in which flotation devices were employed, 58 percent of the boaters survived; among those who did not use flotation devices, only 28 percent were saved.

It seems clear from this investigation that personnel flotation device requirements for recreational boating required serious study, and certain key aspects of this investigation have been addressed.

5. SWIMMING ABILITY OF THE ADULT POPULATION

Data were gathered from discussions with Red Cross personnel who participated in tests of the swimming ability of U.S. military personnel in 1946.

Sixteen thousand troops were tested, who were active adults between 18 and 45 years of age. The results indicated the following:

- One-third could not swim by any minimal standard
- One-ninth could stay afloat for only a few seconds
- Fifty percent could swim or struggle for about fifty yards
- The floating abilities of the men ranged from a few seconds to 1-1/2 minutes
- The capabilities of the men to tread water ranged from 1 to 1-1/2 minutes.

It was assumed that a person falling into chilled water wearing some clothing would not swim as well as could be done in a pool. Therefore, all values obtained were reduced by one-half to represent the swimmer accidently in the water. No data existed on the speeds of swimmers, but it was assumed that a good swimmer could swim at walking speed or about 8 feet a second; an average swimmer about half that speed or about 4 feet a second and a poor swimmer at one-half the average swimmer's speed or 2 feet a second. Further, it was assumed that a good swimmer would be less likely to panic and would float or tread water to conserve energy while a poor swimmer would panic and would struggle until he sank. Figure A-3 shows the ranges of swim distance estimates for the population based upon the initially provided Red Cross data. Figure A-4 shows the Red Cross data and the assumptions used concerning swimming speed.

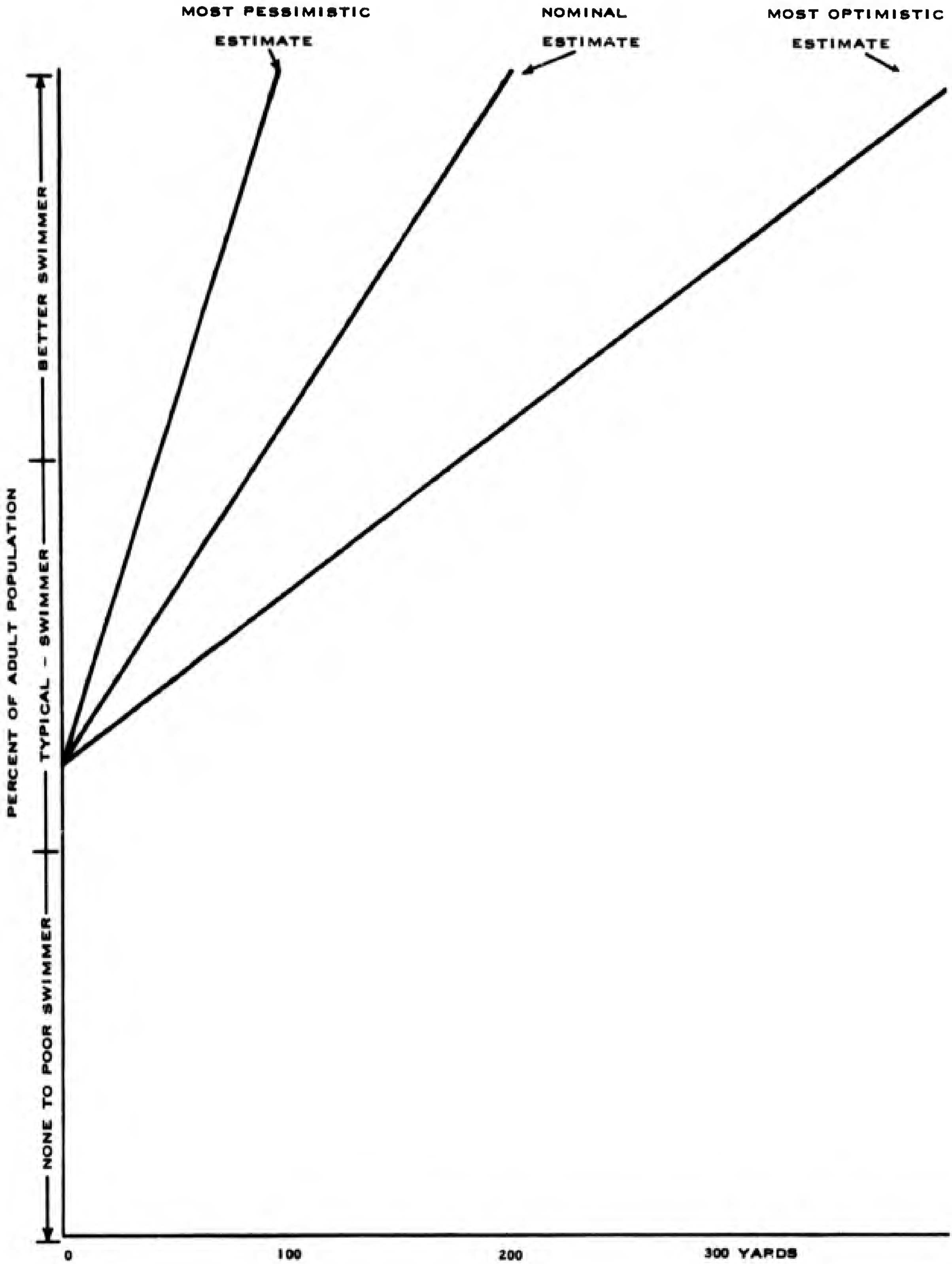


FIGURE A-3. Adult Swimming Endurance - Distance

FIGURE A-4

ADULT SWIMMING ENDURANCE – TIME

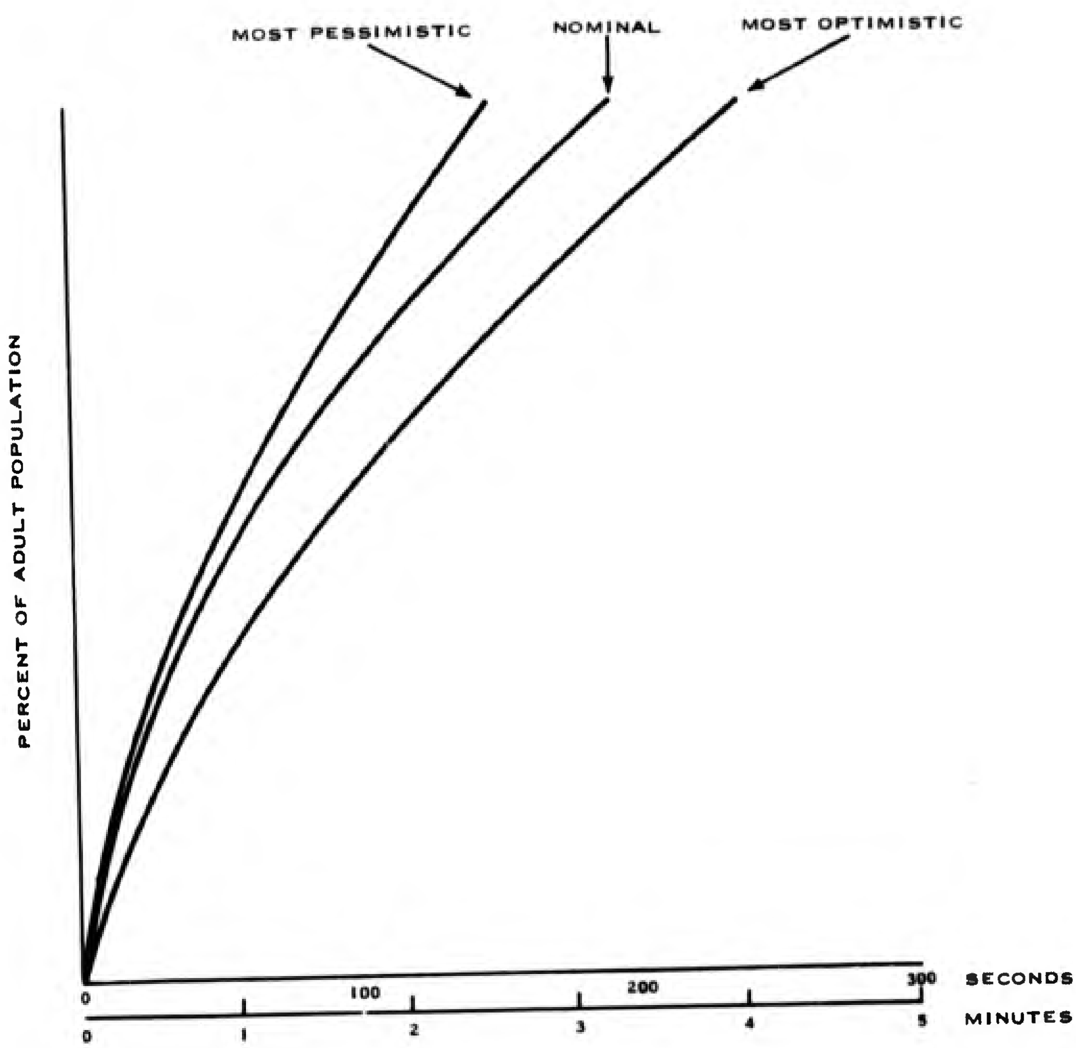


FIGURE A-4. Adult Swimming Endurance—Time

6. ANALYTIC MODELS OF HUMANS USED

Analytic models were developed of the human body to (1) determine the turning moment necessary to keep the floating body at various angles in the water and to (2) determine the forces induced by the exposed head and neck as well as necessary safe body angles. Figure A-5 defines these relationships.

7. ANALYTIC MODELS OF THE BUOYANT SECTION OF A JACKET-TYPE PERSONNEL FLOTATION DEVICE

Figures A-6 and A-7 show the assumed geometric relationships and the location of the buoyant force for a jacket-type personnel flotation device. In addition, the equations used in determining buoyancy and the turning moment or torque are shown on the following page.

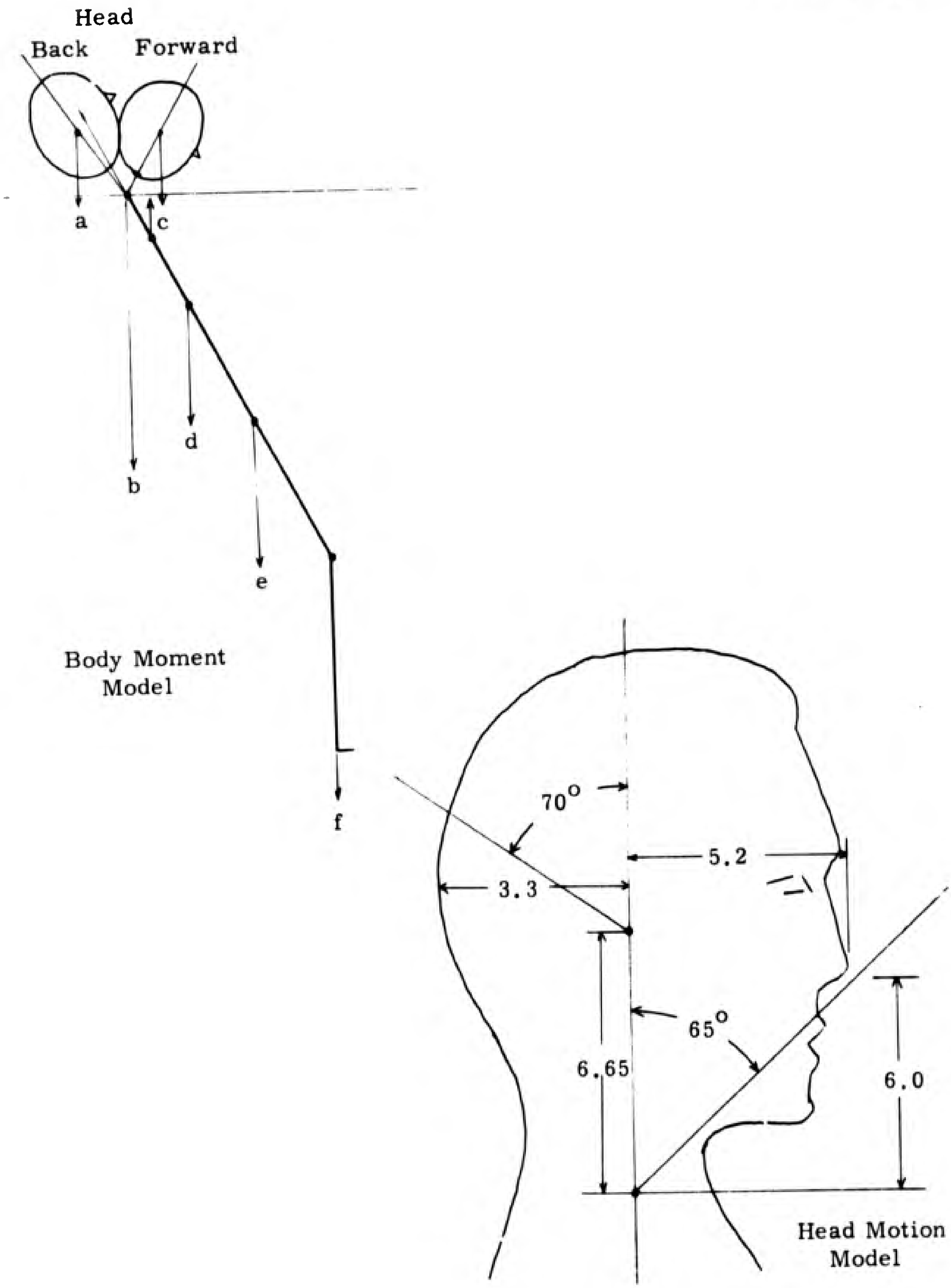


FIGURE A-5. Model of Human Body and Head

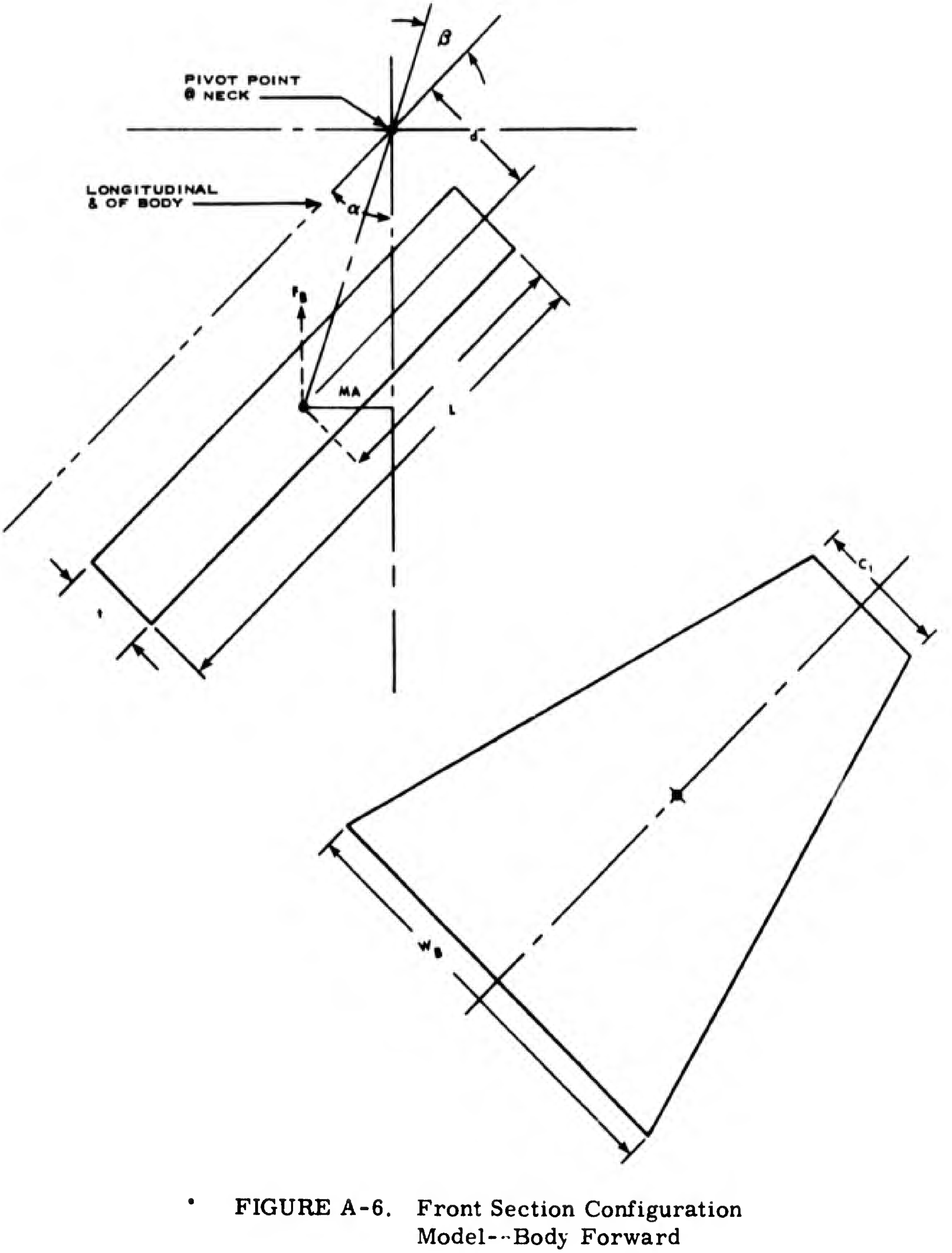


FIGURE A-6. Front Section Configuration Model--Body Forward

1. Buoyancy F_B

(1) $F_B = L \cdot t \cdot \left(\frac{C_1 + W_B}{2}\right) \gamma$ where γ is the buoyant force per in^3 of material

2. Torque (T)

(1) $T = F_B (MA)$ where (MA) is the moment arm of the centroid of the configuration.

(2) $MA = dn \sin(\alpha - \beta) \csc\beta$ where α is body forward inclined angle from vertical

1. $\beta = \tan^{-1} \frac{dn}{l_c}$

(1) $d_1 = 4 + t/2$ for 5%ile, where (t) is material thickness

$d_2 = 6 + t/2$ for 95%ile

(2) $l_c = \frac{2}{3} L \left[\frac{W_B + C_{1/2}}{W_B + C_1}\right]$

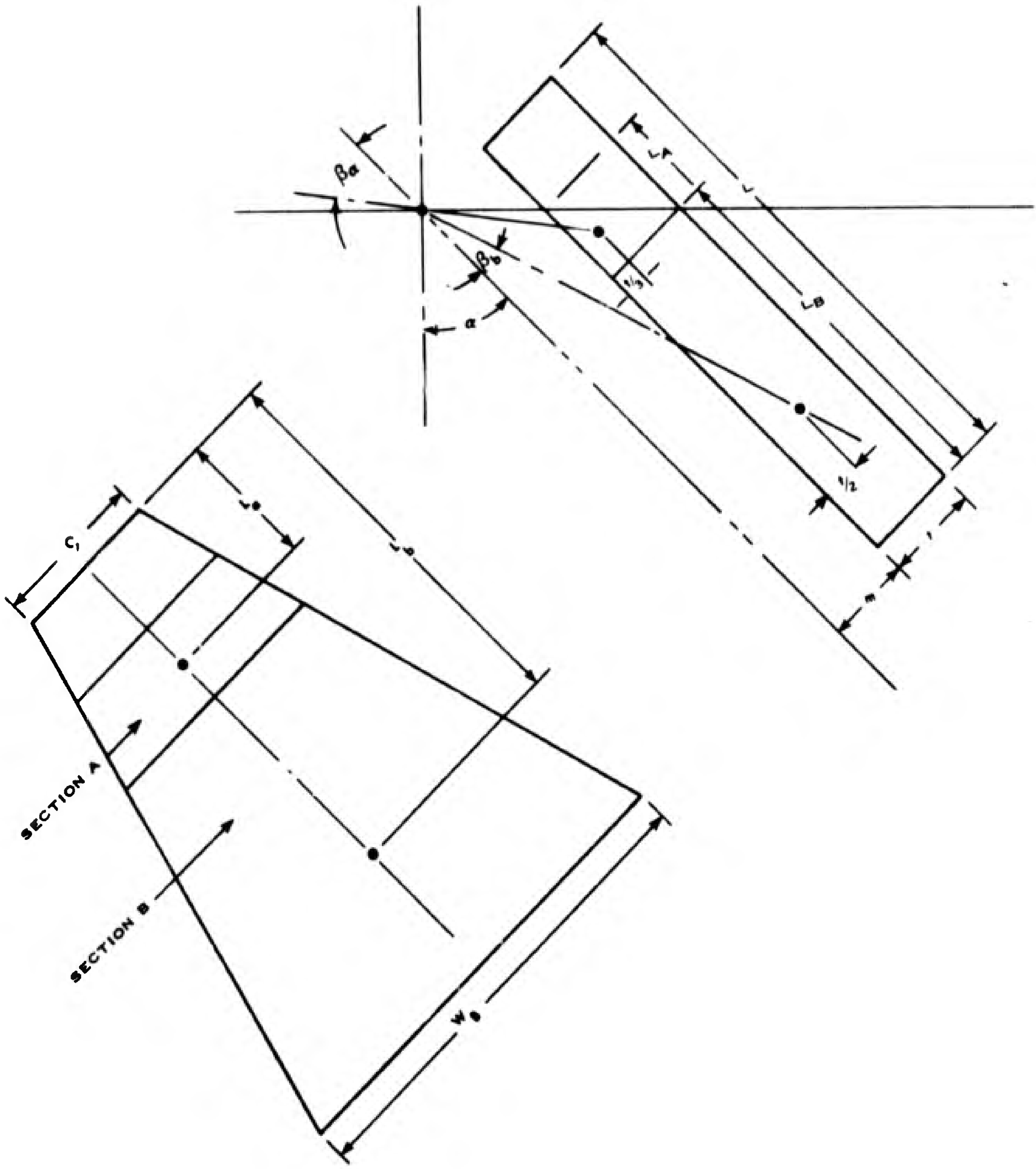


FIGURE A-7. Front Section Configuration Model--Body Backward

1. <u>Buoyancy</u> $(F_B)_A$, for Section A

(1) $$(F_B)_A = \left(\frac{W_1 + W_2}{2}\right) \cdot L_A \cdot t \cdot \gamma$$

1. $W_1 = C_1 + C_2 \, (m \cdot \tan\alpha)$

2. $W_2 = C_1 + C_2 \, (m + t) \tan\alpha$

3. $L_A = t \tan\alpha$

4. $C_2 = \dfrac{W_B - C_1}{2L}$

(2) $$(F_B)_A = \left[C_1 + C_2 \, (m + t/2) \tan\alpha\right] \left[t^2 \tan\alpha\right] \gamma$$

2. <u>Buoyancy</u> $(F_B)_B$, for Section B

(1) $$(F_B)_B = \left(\frac{W_2 + W_B}{2}\right) (L_B) \, t \, \gamma$$

1. $L_B = L - (m + t) \tan\alpha$

(2) $$(F_B)_B = \left[W_B + C_1 + C_2 \, (m + t) \tan\alpha\right] \left[L - (m + t) \tan\alpha\right] t \, \gamma$$

3. <u>Torque</u> (T)

(1) $T = T_a + T_b$

(2) <u>Torque for Section A,</u> (T_a)

$T_a = (F_B)_A \, (MA)_A$

1. Moment Arm for Section A $(MA)_A$

$(MA)_A = dn \left[\sin(\alpha - \beta_A)\right] \csc\beta$, where α is body backward inclined angle from vertical (0 to -90°)

(1) dn

d_1 (5%ile) = $(4 + t/3)$

d_2 (95%ile) = $(6 + t/3)$

(2) $\beta_a = \tan^{-1}\left[\frac{dn}{l_a}\right]$

1. $l_a = \left[\left\{\frac{C_1 + C_2 (m + 2/3\ t) \tan\alpha}{2\left[C_1 + C_2 (m + t/2 \tan\alpha\right]}\right\} t + m\right] \tan\alpha$

m = 4 for 5%ile

6 for 95%ile

2. Moment Arm for Section B $(MA)_B$

$(MA)_B = dn \quad \sin(\alpha - \beta_B) \quad \csc\beta$

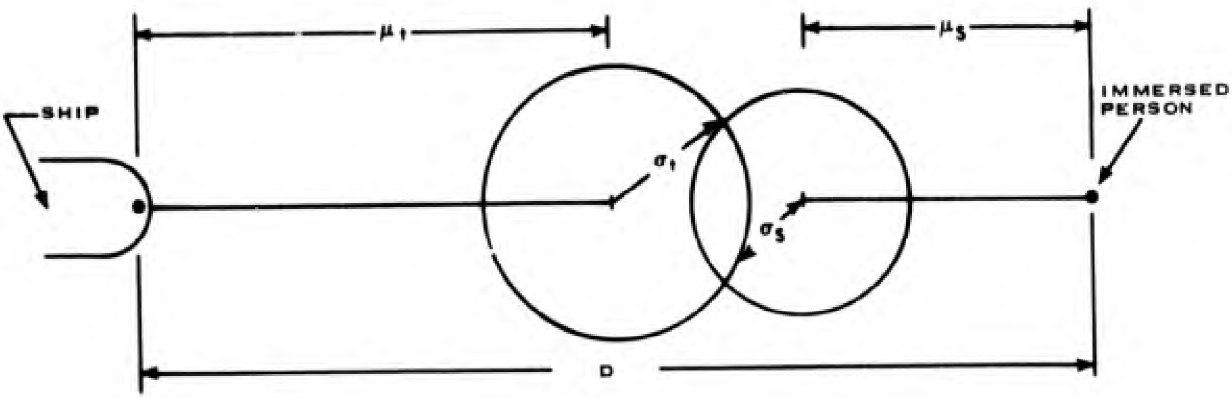
(1) $\beta_b = \tan^{-1} \frac{dn}{l_b}$

1. $l_b\ (m + t) \tan\alpha + (L - (m + t) \tan\alpha)$

$$\left[\frac{2W_B + C_1 + C_2 (m + t) \tan\alpha}{3W_B + C_1 + C_2 (m + t) \tan\alpha}\right]$$

8. THROW-TYPE DEVICES ANALYSIS

The model used to assess the probability that a swimmer could reach a device thrown to him is shown on the following page. The model did not consider the condition of a device thrown past the swimmer. Further, it did not include wind effects upon throw accuracy (σ_t) nor upon the wind induced drift of a floating personnel flotation device. Figure A-8 shows the model and equations used in this analysis.



P_{SOR} – PROBABILITY OF SURVIVAL = "t", WHERE STUDENT'S t

EQUALS:

$$P_{SUR} = \frac{D - [\mu_t + \mu_s]}{[\sigma_t^2 + \sigma_s^2]} = t \text{ WHERE}$$

μ_t – THROW DISTANCE MEAN

σ_t – THROW DISTANCE MEAN STANDARD DEVISION (THROW ACCURACY)

μ_s – SWIMMING DISTANCE MEAN

σ_s – SWIMMING DISTANCE MEAN STANDARD DEVIATION

D – DISTANCE BETWEEN SHIP AND IMMERSED PERSON

D = Vt WHERE V IS SHIP SPEED, IN FEET PER SECOND
AND t IS ACCESS TIME, IN SECONDS

FIGURE A-8. Throw Type PFD Model

9. CHARACTERISTICS OF BUOYANT MATERIALS

The following discussion focuses on the characteristics of principal plastic materials.

(1) Urethane Foams

There are many types of urethane, in both rigid and flexible form. The flexible form of urethane is an open-cell material and cannot be considered as an acceptable foam plastic for life preserver buoyant material unless an acceptable hydrophobic capability can be added to the flexible urethane.

Urethane foams are produced by the exothermic reaction of a polyisocyanate and a polyol, in the presence of a catalyst, plus a surfactant and a foaming or blowing agent. The choice of polyol has a major influence on the physical properties of the foam; it determines whether the resulting foam will be rigid or flexible, brittle, or non-brittle, and the extent of its permeability to gas and moisture. It appears that during the formation of the flexible foam, as the last surge of gas is released, the membranes of the foam have a high viscosity but very low elasticity. The combination of a steadily rising gas pressure and the failure of the cell to expand fast enough because of the high viscosity and low mechanical strength results in rupture of the cells and the consequent open-cell structure.

The foam plastic is cooled and reheated to 200 degrees F to ensure that the pressure within each cell is equalized. Finally, an annealing operation is performed by reheating the foam to 150 degrees F to avoid shrinkage of the foam in service.

(2) Polyethylene Foam

There are two basic types of polyethylene foam available today: a high-density foam, 20 to 30 lb/cu. ft., and a low-density foam, about 2 lb/cu. ft. The low-density foam has acceptable physical properties for the buoyant material of a personnel flotation device. The low-density polyethylene foam can be made into a soft unicellular configuration with low-burning-rate or self-extinguishing flammability characteristics.

Low-density polyethylene foam is made by mixing a foaming agent with hot, molten polymer under pressure, with subsequent pressure reduction and cooling. The cell structure can be varied by controlling and cooling time and, in certain cases, application of ionizing radiation. The foam plastic can be produced in molded form, as well as in sheet form. Application of hot metal to the exposed surface of the foam will result in a thin protective skin coating.

3. VINYL FOAMS

Vinyl foams vary extensively in their physical properties. The softness or rigidity, density, and cell structure can be varied from one extreme to the other. Vinyl foam can be made in a soft, closed-cell form which has excellent properties for the buoyant material of a personnel flotation device. Polyvinyl chloride (PVC) is a foam plastic approved by the United States Coast Guard as a buoyant material.

Vinyl foam is produced by introducing air or an inert gas into the vinyl plastisol. This can be done either by mechanical or chemical blowing. The mechanical blowing process involves the dissolving of gas, under pressure, into the plasticizer portion of the vinyl plastisol and subsequently, allowing the system to expand rapidly at atmospheric pressure, after which it is fused under heat. A second mechanical process consists of whipping air into a specially formulated plastisol, of which part is a surfactant containing a stabilizer. Both mechanical processes produce an open-cell configuration of vinyl foam. The closed-cell configuration is produced by chemical blowing. In this process, vinyl foam is prepared under high pressure, in which a variety of blowing agents can be used. The plastic is heated to about 350 degrees F, under pressures between 4000 to 10,000 psi. Under these conditions, the blowing agent is decomposed, with gas distributed as small cells.

(4) Polystyrene Foam

The bulk of styrene foam in use today is a type based upon expandable polystyrene beads. Polystyrene is a poor candidate for the buoyant material of a life preserver since it is relatively inelastic, with poor flexure characteristics, and has poor structural integrity properties, i.e., it can readily be flaked or separated into segments.

Polystyrene foam is produced by a suspension polymerization process in which the blowing agent is either incorporated into the styrene during polymerization or the blowing agent is dispensed into the suspension polymerized styrene under heat and pressure. The basic type of foam is the expandable polystyrene beads. By heating the beads to a temperature of about 200 degrees F, the internal pressure of the blowing agent causes the beads to expand to as much as 50 times their volume. A recent development in styrene foams is styrene copolymers, of which the most notable has been styrene-acrylonitrile (SAN) copolymers. The advantage of the copolymers is a greater chemical resistance than conventional polystyrene foams. However, their physical properties are essentially the same as polystyrene.

Table A-4
Foam Plastics Characteristics

Properties \ Foam Plastic	Urethane	Polystyrene	Vinyl (PVC)	Polyethylene	Phenol	Epoxy	Silicones (RTV)	Cellular Cellulose Acetate
Water Absorption (a)	0	2	2	2	0	2	0	1
Flammability (b)	2*	2*	2	1	2	2	2	1
Pliability (c)	2	0	1	1	0	0	2	0
Structural Integrity (d)	1	0	2	2	0	2	1	2
Buoyancy (e)	2	2	2	2	2	2	0	1

Legend:

(a) Water absorption rating

(2) Nil to low (0-5% by volume material)
(1) Low to moderate (6-15% by volume of material)
(0) High (16% plus by volume of material)

(b) Flammability rating

(2) Self-extinguishing
(1) Slow burning
(0) Burns at a rate greater than 0. 5 in. /sec.

Table A-4
Continued

(c) Pliability rating

- (2) Highly elastic--low spring coefficient
- (1) Elastic--moderate spring coefficient
- (0) Unelastic--crushable

(d) Structural integrity rating

- (2) Strong cohesion
- (1) Moderate cohesion
- (0) Poor to no cohesion

(e) Buoyancy rating

- (2) 0.1 to 5 lbs/ft^3 density
- (1) 6 to 10 lbs/ft^3 density
- (0) over 11 lbs/ft^3 density

* Foam plastic has acceptable flammability properties when proper additives are used in the manufacture of the material.

10. ORGANIZATIONS CONTACTED

The following is a partial listing of those organizations contacted in the course of this study:

Adolph Kiefer and Associates, 2040 Suffork Road, Northfield, Illinois

American Red Cross, District of Columbia Chapter

Arkon Products, Connecticut

Atlantic-Pacific Manufacturing Corporation, 124 Atlantic Avenue, Brooklyn, New York

B.F. Goodrich, Foam Plastics Div., Connecticut

The Dow Chemical Company, New York

The Empress Corporation, 110 West 11th Street, Los Angeles, California

Ero Industries, 712 West Monroe, Chicago, Illinois

Gentex Corporation, Carbondale, Pa.

Lifegard Manufacturing Corp., P.O. Box 49, Dewitt, N.Y.

One Design Specialties, Inc., 3100 East Washington St., Rt. 37, Toms River, New Jersey

Ripley Marine Supplies

Ski Swim, Division of Cal-June Corp., P.O. Box 9551, North Hollywood, California

Switlik Parachute Co., Inc., 1325 East State Street, Trenton, New Jersey

Texas Water Crafters, Wichita Falls, Texas

Union Carbide Corporation, Plainfield, New Jersey

U. S. Coast Guard

Testing and Development Division

Recreation Boating Division

Auxiliary Division

Merchant Marine Technical Division

The U. S. Navy, Air Safety Center, Norfolk, Virginia

The U. S. Navy, Naval Air Systems Command, Washington, D. C.

The U. S. Navy, Ships Parts Control Center, Mechanicsburg, Pa.

The Yacht Safety Bureau, New Jersey