

# Risk Models for Evaluation and Type Classification of Personal Flotation Devices

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*This paper presents proposed models for assessing the aggregate performance of personal flotation devices (PFDs) by using risk methods. The aggregate performance is used to quantify the probability of a PFD saving lives following marine events. The models provide a formal structure and consistency to an approval process for new and novel engineering designs of such devices. They can also aid in identifying critical factors for evaluating the minimum level of performance necessary for approval. Such models could complement and enhance current standards and could result in significant safety improvements through the implementation of new technologies and designs. Such models could also aid in evaluating other new and innovative classes of engineering designs and designs for special needs. Also, they encourage creativity in system design by increasing the design domain and provide an overall performance measure allowing for trade-off analysis. The models can ultimately provide guidance in the development of future standards. The risk-based models consist of three recommended computational procedures for inherently buoyant, inflatable, and hybrid PFDs. Special panels of experts from the CORD Group, Canada, the U.S. Coast Guard (USCG), Underwriters Laboratories (UL), IMANNA Laboratories, Inc., and PFD Manufacturing Association (PFDMA) evaluated these models and provided recommended values by using formal expert opinion elicitation. [DOI: 10.1115/1.4026399]*

**Keywords:** life jackets, personal flotation devices, drowning, human life, compliance, standards, decision making, flotation, rescue, lifesaving

## 1 Introduction

**1.1 Accidents and Fatalities.** The USCG compiles statistics every year on reported recreational boating accidents on the basis of accident reports filed by people involved in these accidents and produces an annual boating statistics publication. The 2011 USCG publication [1] reports 4588 accidents involving 758 deaths, 3081 injuries, and approximately \$52 million in damage to property from these accidents. The reported fatality rate was 6.2 deaths per 100,000 registered recreational vessels; there were 12,173,935 recreational vessels registered. Seventy percent of all fatal boating accident victims drowned, 84% of whom were reported as not wearing a life jacket or PFD. Eighty percent of those who drowned were using vessels less than 21 ft long. In 16% of deaths, alcohol use was the leading contributing factor. Sixty percent of the children fatalities were from drowning, with 78% of those who drowned were reportedly wearing life jackets as required by state and federal law. The most common types of vessels involved in reported accidents were open motorboats (47%), personal watercraft (19%), and cabin motorboats (14%). It is noteworthy that nine out of ten drowning cases occur in inland waters, on days of good weather, and most within a few feet of safety (see Table 1). Tragically, most drowning victims had access to a PFD but did not wear it.

**1.2 PFD Regulations, Standards and Design Domains.** The design, manufacturing and in-water performance of PFDs are regulated by the USCG and standardized through consensus by stakeholders from the industry, the government, test and standards organizations, safety organizations, commercial users, supply chain, consumers, and general interest. The PFD standards in the United States are managed by UL, with standards such as UL

1123 [2], UL 1180 [3], and UL 1517 [4]. Personal flotation devices are tested for performance by USCG-certified laboratories before their USCG approval for use. Moreover, the manufacturing and production of PFDs are overseen by the same laboratories that conduct the approval testing for USCG-certified manufacturers.

Personal flotation device standards provide guidance and requirements on in-water performance and some design aspects of PFDs to ensure a survival likelihood from drowning that is greater than some acceptable levels. Establishing and defining the PFD performance characteristics needed to meet this goal for various users and environments is schematically shown in the partitioned spaces of Fig. 1. Ideally the standards would cover the full area of the four quadrants, but realistically this is not economically or technologically possible; therefore, the regulators and the industry seek to cover universal and unique factors for survival. All PFD designs should address common factors based on “universal needs” as shown in the figure, e.g., minimize the time that breathing is impeded. In some circumstances, some PFDs must also address special conditions indicated as “universal needs and unique conditions” in the figure, e.g., thermal protection needs, special restraint or recovery harness, or needs of a broader range of body types than the majority of the population. Acceptable performance becomes a variable based on the different users, environments, and applications for the PFDs, or on the combined performance according to several individual test characteristics. The current state of PFD requirements as defined by governing standards, called “possible states per current PFD standards” in the figure, should be assessed in comparison with the “universal needs and unique conditions.” The figure also includes “unfeasible conditions” to identify the space outside the “universal needs including unique conditions” space, e.g., swift water entrapment. To define these needs and the significance of the specific requirements for PFD performance, risk and reclassification (PFDRRA) models are proposed in this paper to aggregate in-water effectiveness of PFDs. In this paper, they are called PFDRRA models.

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**Table 1 Weather and water conditions [1]**

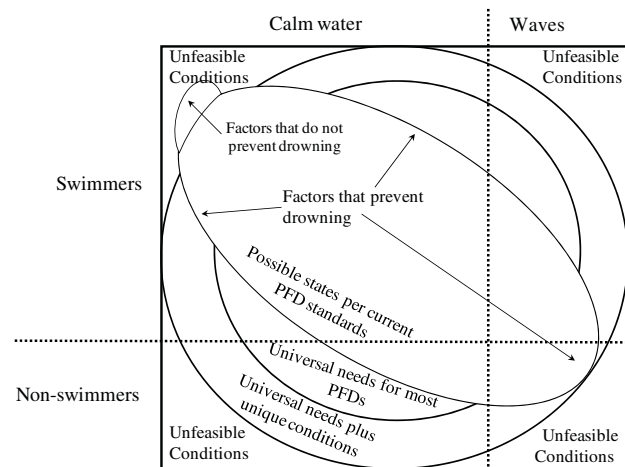
Case	Item	Accidents	Deaths	Injuries
		4588	758	3081
Type of water body	Inland waters (lakes, bays, rivers, etc.)	89.1%	91.4%	89.7%
	Great lakes, gulf, and oceans	10.9%	8.6%	10.3%
	Unknown	0.0%	0.0%	0.0%
Water conditions	Calm (waves less than 6 in.)	54.1%	49.7%	55.6%
	Choppy (waves 6 to 24 in.)	28.3%	23.1%	30.1%
	Rough and very rough	12.0%	14.8%	9.8%
	Unknown	5.7%	12.4%	4.5%
Wind	None	9.2%	12.1%	9.6%
	Light (0–6 mph)	54.7%	46.4%	60.3%
	Moderate (7–14 mph)	22.8%	19.0%	21.0%
	Strong and storm	9.2%	12.9%	5.6%
	Unknown	4.1%	9.5%	3.4%
Visibility	Poor	4.2%	5.7%	4.5%
	Fair	6.5%	8.3%	5.7%
	Good	82.0%	74.7%	83.5%
	Unknown	7.3%	11.4%	6.3%
Water temperature	30°F and below	1.1%	3.6%	1.1%
	40–49°F	3.0%	8.2%	2.4%
	50–59°F	8.1%	15.0%	8.0%
	60–69°F	16.8%	17.7%	15.1%
	70–79°F	30.0%	19.8%	30.3%
	80–89°F	24.1%	17.7%	26.5%
	90°F or above	1.6%	1.2%	2.0%
	Unknown	15.4%	16.9%	14.6%

**1.3 Background.** The models are derived from event and fault tree modeling of all possible scenarios following a marine event [5–7] and are updated to reflect dependency among underlying events [8–10]. These models provide a formal structure and consistency to the process of evaluating new and novel approaches to designing devices for drowning prevention and designs for special needs. They can be used within a risk-based compliance approval process, identifying critical factors for evaluating a PFD's lifesaving potential and can be applied to determine the minimum level of performance necessary for approval of PFD design by an authorized test laboratory or a regulatory agency. Also, they encourage creativity in system design and provide an overall performance measure allowing for trade-off analysis. The models complement and enhance the current PFD standards and can ultimately provide a basis for the development of future standards.

The models presented in this paper were calibrated and beta tested by users from various industry sectors in 2002 [9]. In several

beta-testing studies, the models were used to evaluate the performance of specific USCG-approved PFDs to determine implicit life-saving probabilities in these designs. The calibration process enabled the determination of target probabilities based on minimum design and performance characteristics of PFDs. The PFDRA models consist of three recommended computational procedures for inherently buoyant, inflatable, and hybrid PFDs. A special panel of subject matter experts from the U.S. Coast Guard and Transport Canada, industry representatives from the PFD Manufacturer Association (PFDMA), Underwriter Laboratories, Inc., IMANNA Laboratories, Inc., and others, has evaluated this methodology in several workshops of subject matter experts, PFD beta testing, and validation [11–14].

**1.4 Purpose and Scope.** The proposed models are: (1) for the type evaluation of conventional PFDs, i.e., performance, classification and aggregation of in-water effectiveness of personal flotation devices and (2) for evaluation of special-purpose life jackets and buoyancy aids that perform accordingly for special-use applications or provide equivalent performance. These applications and equivalences should not reduce essential requirements, such as aggregate












**Fig. 1 PFD performance, design domain, and standards**



**Fig. 2 An early cork life jacket design of 1861 [15]**

**Table 2 Types of personal flotation devices in the United States**

PFD device type and image	Description
<p>Off-shore life jackets (USCG Type I PFD)</p>  <p>(a) Inherently buoyant vest Type I</p>	<p>Designed for open, rough, or remote waters, where rescue may not be immediate. Such PFDs provide the most reliable flotation, turn most unconscious wearers face-up, come in highly visible colors, and may have reflective material for search and rescue. They are, however, bulky and could restrict full range of movements needed to enjoy water-related activities and sports.</p>
<p>Near-shore buoyant vests (USCG Type II PFDs)</p>  <p>(b) Inherently buoyant vest Type II</p>  <p>(c) Inflatable vest Type II (deflated)</p>  <p>(d) Inflatable vest Type II (inflated)</p>	<p>Designed for calm or inland water, where fast rescue is likely. Such PFDs turn some unconscious wearers face-up in the water, are less bulky and more comfortable than off-shore life jackets (Type I PFDs), are approved for multiple sizes from infant through adult, a good choice for children, and are suitable for some rough water conditions. They are, however, not recommended for long hours in rough water and can be uncomfortable or cumbersome for adults to wear. The wearer's face may often be covered by water from waves.</p>
<p>Flotation aids (USCG Type III PFDs)</p>  <p>(e) Inherently buoyant Type III</p>  <p>(f) Inflatable belt Type III (deflated)</p>  <p>(g) Inflatable vest Type III (deflated and inflated)</p>	<p>Designed for conscious users in calm inland water or where fast rescue is likely. Such PFDs are generally the most comfortable for continuous wear, are designed for general boating and designated activities marked on the device, and are available in many styles, including vests and flotation coats. Wearers, however, may have to tilt the head back to avoid being floated face-down, and these devices are not recommended for extended survival in rough water. The wearers' face may often be covered by water from waves.</p>
<p>(h) Throwable devices (USCG IV PFDs)</p> 	<p>Includes buoys and boat cushions. They function as throwable devices and are not designed to be worn.</p>
<p>(i) Wearable special-use devices (USCG Type V PFDs)</p> 	<p>Includes boardsailing vests, deck suits, pullover vests, work vests, some hybrid PFDs, etc.</p>

All images were provided courtesy of Mustang Survival ULC.




Pictogram concept (derived from ISO PFD standards)	Descriptive Name	Descriptive definition (Simple, clear descriptions of environment for users)
	Open Water (OW) Life jacket	Designed for open, rough or remote water, where rescue may be slow coming: <ul style="list-style-type: none"> <li>• Most effective for offshore waters.</li> <li>• Turns most people from face down to face up.</li> <li>• Best chance of survival for unconscious wearer.</li> <li>• Enhances detection with features such as highly visible color.</li> </ul>
	Near Shore (NS) Life jacket	Designed for calm or inland water, or where there is good chance of fast rescue: <ul style="list-style-type: none"> <li>• Good support for unconscious wearer.</li> <li>• Will turn some people from face down to face up.</li> <li>• Available for adults and children</li> </ul>
	Calm water (CW) Buoyancy Aid	Designed for conscious users in calm, inland water, or where rescue is close at hand: <ul style="list-style-type: none"> <li>• Most comfortable with less bulk, to encourage continuous wear.</li> <li>• Many suitable for water sports.</li> <li>• Not for smallest children.</li> <li>• Will not turn unconscious user from face down to face up.</li> </ul>

Fig. 3 Environments for PFDs

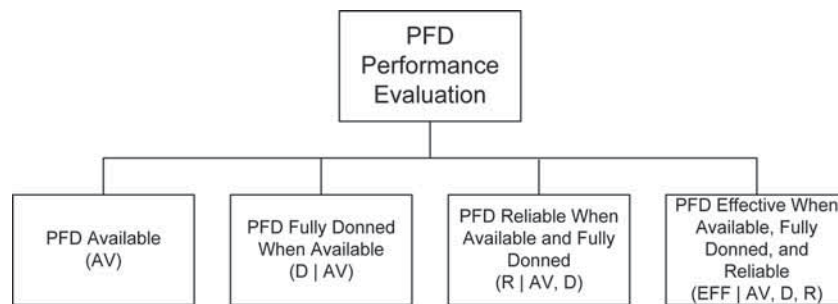


Fig. 4 PFD performance evaluation

Table 3 Parameters relating to PFD performance effectiveness for all buoyancy methods and environments

Notation	Name	Measurement definition
EFF	P(EFF AV, D, R)	Probability that the PFD is effective given that the PFD is available, donned, and reliable. This event is affected by the following performance characteristics:
FB	Freeboard	Distance measured perpendicular to the surface of the water to the lowest point where the wearer's respiration may be impeded. The model values are based on the average of all subjects tested without any negative values permitted.
HP	Heave period	When a subject wearing a PFD, face-up, and in a relaxed position is forcefully submerged in calm water, the heave period is the time it takes the subject to transcend one immersion-emersion cycle. The model value is based on the result of testing one specific subject.
TT	Turning time and ability	For life jackets, turning time measures turning ability and is defined as the average time required for a device to turn face-down wearers to a position in which the wearers' respiration is not impeded by water, corrected for the percentage of turns $[TT = (A_t) \text{ the average turning time for all tests resulting in a turn } x (T_{\text{total}}) \text{ total number of tests performed} / (T_t) \text{ the number of tests resulting in a turn}]$ . For buoyancy aids, each subject passing the stability test is required to obtain a value of 1 for this characteristic. Otherwise, the value is zero, and the device rejected.
FPA	Face plane angle	The angle, relative to the surface of the water, of the plane formed by the most forward part of the forehead and chin of a wearer floating in the attitude of static balance. A positive angle is achieved when a user's forehead is higher than their chin. Model values are based on the average of all subjects tested.
PS	Placement security	For buoyancy aids the ride-up test is used as a current gauge of the PFD placement security. Ride-up is defined as the shoulder gap measured between the device and the right shoulder of the subject following three self-induced plunging actions in the water while in the vertical position. Model values are based on the average of all subjects tested. For life jackets, passing the water entry test is required to obtain a value of 1 for this characteristic. Otherwise, the value is zero, and the device rejected.
DTC	Detectability	Availability, adequacy, and effectiveness of detection aids for a PFD user, measured as the probability of detection of a user by rescuers. Model values are based on the PFD design and certain accessories provided.

**Table 4(a) Parameters for all environments and all PFDs**

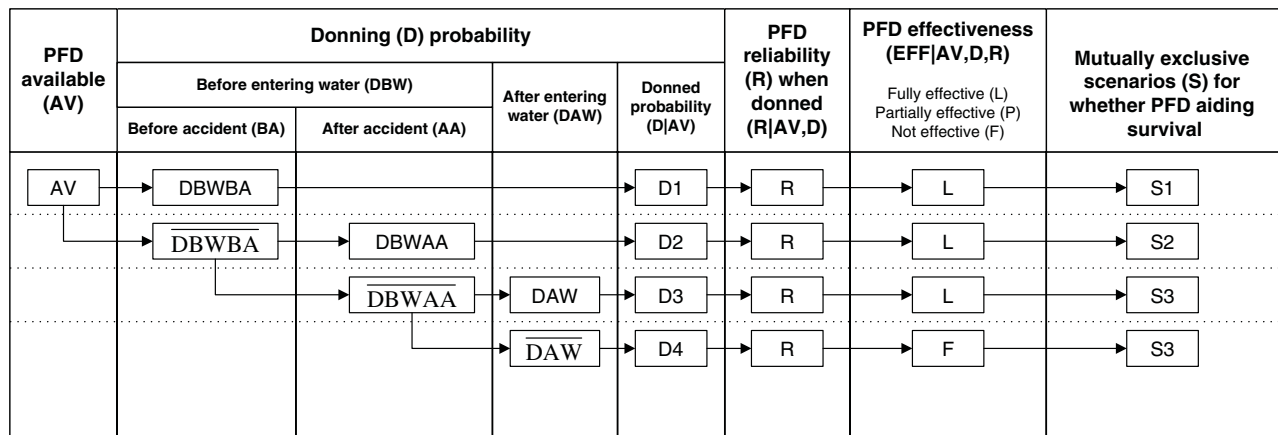
Notation	Name	Measurement definition
BME	Buoyant material effective	The fraction of the adult population for which the buoyant chamber/buoyancy material will provide sufficient flotation to keep airway above the surface in calm water and adjusted for various environments.
DA	Don PFD after entering the water	The probability that the PFD wearer dons a PFD that accounts for the average time to don in calm-water condition and the wearer is a swimmer. DA is outside the scope of the present practice, and its values are a multiple of the DP respective values.
DP	Don PFD before entering the water	The probability that the PFD wearer dons a PFD that accounts for the average time to don before entering water. This probability can be estimated from testing the average time to don a PFD out of water.
PMB	PFD maintains buoyancy	The probability that the PFD maintains buoyancy during usage under the condition that it survives the marine event. Reliability for the buoyancy chamber and material is estimated by performing a submergence buoyancy test and measuring the loss over time (24 hr) as well as performing the component buoyancy durability tests.
ROC	Other components vital to providing buoyancy operate	Probability that the other components vital to providing buoyancy operate, such as straps, buckles, adjusters, zips, etc.
SNDF	Shell not defective	Probability that the shell fabric/material is not defective.
SNDMB	Shell not defective before entering water	Probability that the shell fabric/material is not damaged before entering the water.
SNDMA	Shell not damaged after entering water	Probability that the shell fabric/material is not damaged after entering the water.
W	Wearability	Probability that a PFD is worn during a marine event given that the person has the skills and knowledge to don before an accident. This probability is affected by the subjective judgment of PFD wearers who are influenced by things such as the aesthetics and utility of the PFD design.

**Table 4(b) Parameters for all environments and for only inflatable and hybrid PFDs**

Notation	Name	Measurement definition
AAF	Automatic activation functions	The automatic activation-inflation system is a system that activates to inflate one or more PFD compartments upon immersion in water without any action by the user. This probability can be estimated from the time it takes to automatically activate a PFD once it enters the water.
CASA	Gas does not exceed design pressure	Probability that the compressed gas does not exceed the burst pressure of the PFD upon activation. The limits shall be established by overpressure testing PFDs to ensure compliance with UL or ISO requirements.
CLPA	Cylinder properly loaded (auto-inflation)	Probability that the gas cylinder is properly loaded for automatic activation. This probability should account for the presence of a cylinder seal indication device.
CLPM	Cylinder properly loaded (manual)	Probability that the gas cylinder is properly loaded for manual activation. This probability should account for the presence of a cylinder seal indication device.
CNDA	Cylinder not defective (auto-inflation)	Probability that the cylinder is not defective to properly inflate for automatic activation.
CNDM	Cylinder not defective (manual)	Probability that the cylinder is not defective to properly inflate for manual activation.
CNPAA	Cylinder not activated (auto-inflation)	Probability that the cylinder was not previously activated for automatic inflation. This probability should account for the use of cylinder seal indication.
CNPAM	Cylinder not previously activated (manual)	Probability the cylinder was not previously activated for manual activation. This probability should account for the use of cylinder seal indication.
MAMF	Manual device functions before entering water	Probability that the manual activation functions before entering the water. This probability accounts for several events including the probability of mechanical device functions (MDF) and the probability that the wearer activates the device (PACB). It can be estimated from the time it takes an individual to manually activate the PFD while out of the water.
MAMFA	Manual device functions after entering water	Probability that the manual activation functions after entering the water. This probability accounts for several events including the mechanical device functions after entering the water (MDFA) and the probability that the wearer activates the device after entering the water. This probability can be estimated from the time it takes an individual to manually activate the PFD while in the water.
MAWA	Mouth activation using oral inflator (after entering water)	Probability that the oral inflation system functions, accounting for several events including the probability that the mechanical mouth activation system functions and the probability that the person has the knowledge to activate the PFD. This can be estimated from the time it takes an individual to orally inflate the PFD in the water to obtain positive freeboard.
MAWB	Mouth activation using oral inflator (before entering water)	Probability that the oral inflation system functions, accounting for several events including the probability that the mechanical mouth activation system functions and the probability that the person has the knowledge to activate the PFD. This can be estimated from the time it takes an individual to orally inflate the PFD out of the water to obtain positive freeboard when used in water.
RVF	Relief valve functions	Probability that the relief valve is functioning properly. This parameter can be estimated from laboratory tests of the valve's crack pressure.

**Table 5 Parameters relating to PFD users for all buoyancy methods and environments**

Notation	Name	Measurement definition
AV	PFD available	Probability that the PFD is available for use by a person in need
CA	Person conscious after entering water	Probability that a person is conscious after entering water
CP	Person conscious   out of water	Probability that a person is conscious before entering water
EDI	Environment does not impair donning in water	Probability that the environment does not impair donning the PFD while in the water
ENV	Environment does not impair swimming	Probability that the environment does not impair swimming
KS	Skill/knowledge to swim	Probability that a person has the skill and knowledge to swim, i.e., a swimmer
ME	Marine event	Probability that a marine event occurs resulting in immersion
NFI	Person not fatigued   in water	Probability that a person is not fatigued after surviving water entry, shortly after entering the water
NFO	Person not fatigued   out of water	Probability that a person is not fatigued before entering the water
NH	Person not handicapped out of water	Probability that a person is not handicapped (good physical condition) before entering the water
NHI	Person not handicapped in water	Probability that a person is not handicapped (good physical condition) while in the water
NII	Person not injured   in water	Probability that the person is not injured while in the water
NINTI	Person not intoxicated   in water	Probability that the person is not intoxicated while in the water
NINTO	Person not intoxicated   out of water	Probability that a person is not intoxicated before entering water
NIO	Person not injured   out of water	Probability that a person is not injured before entering water



**Fig. 5 Probability tree of inherently buoyant PFD success scenarios**

**Table 6 Definition of events for inherently buoyant PFDs**

Top event	Definition	Basic events
DBWBA	Donning before entering the water and before an accident	DP * W
DBWAA	Donning before entering the water and after an accident	CP * NFO * NH * NIO * NINTO * DP
DAW	Donning after entering the water	NFI * NHI * NII * NINTI * CA * KS * ENV * EDI * DA

in-water performance, stability, and safety in use compared with conventional designs.

This paper presents models for evaluating the aggregate in-water performance of PFDs using risk and reclassification analysis and computational procedures for assessing the probability that a device saves lives. The models assess the ability of PFDs to save lives following marine events by providing a formal structure and consistency for certification consideration of new and novel PFD designs as well as providing aggregate performance assessment for more conventional designs. The models can also aid in identifying critical factors for evaluating the minimum level of performance necessary for certification. The models, therefore, complement and enhance existing standardized requirements and could result in significant safety improvements through the implementation of new technologies and designs.

## 2 Life Jacket History and Types

Since its early days of inception (about 1861) per Fig. 2 [15], life jackets were designed to keep a person afloat in the water

and give the extra time needed to survive an accidental entry into water. It does not take long to drown. According to the PFD Manufacturer Association in their pamphlet at <http://www.pfdma.org/local/downloads/documents/pfdmabrochure.pdf>, it only takes about 60 s for an adult to drown and about 20 s for a child to drown.

The USCG requires approved PFDs on all recreational boats and regulates the design and manufacturing of PFDs. The approval of PFDs is based on meeting a set of performance requirements as defined in consensus standards maintained by UL and testing

**Table 7 Definition of scenarios for inherently buoyant PFDs**

Donning scenario	Scenario definition used as intermediate events	Corresponding effectiveness
D1	DBWBA	Full effectiveness (L)
D2	DBWBA * DBWAA	Full effectiveness (L)
D3	DBWBA * DBWAA * DAW	Full effectiveness (L)
D4	DBWBA * DBWAA * DAW	Ineffectiveness (F)

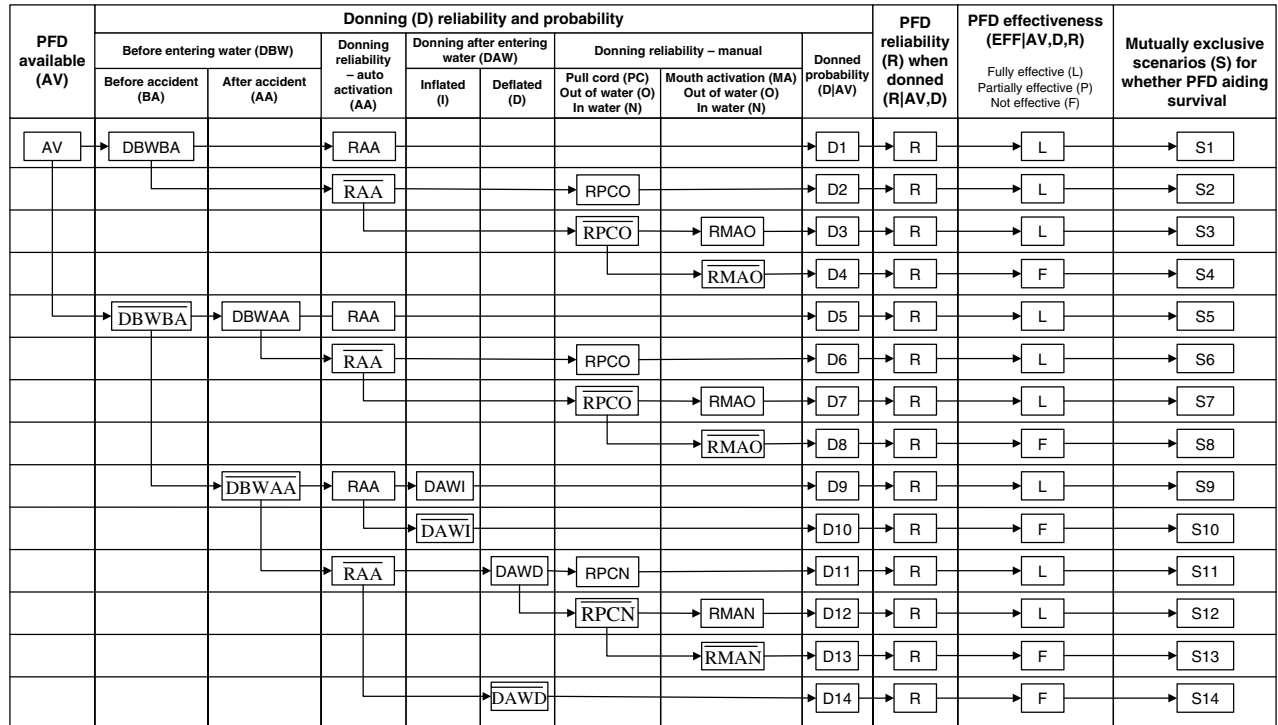


Fig. 6 Probability tree of inflatable PFD success scenarios

Table 8 Definition of events for inflatable PFDs

Top events	Definition	Basic events
DBWBA	PFD donned before entering water before accident	DP * W
DBWAA	PFD donned before entering water after accident	CP * NFO * NH * NIO * NINTO * DP
DAWI <sup>a</sup>	PFD donned after entering water, inflated	NFI * NHI * NII * NINTI * CA * KS * ENV * EDI * DA
DAWD <sup>a</sup>	PFD donned after entering water, deflated	NFI * NHI * NII * NINTI * CA * KS * ENV * EDI * DA
RPCO	Reliability of gas mechanism before entering water by pulling inflation cord	CP * NFO * NH * NIO * NINTO * SNDF * SNDMB * (CASA + RVF – CASA * RVF) * CLPM * CNDM * CNPM * MAMF
RMAO	Reliability of mouth activation mechanism before entering water	CP * NFO * NH * NIO * NINTO * SNDF * SNDMB * MAWB
RAA	Reliability of automatic activation	AAF * CLPA * CNDA * CNPAA * SNDF * SNDMB * (CASA + RVF – CASA * RVF)
RPCN	Reliability of gas mechanism after entering water by pulling inflation cord	CA * NFI * NHI * NII * NINTI * CLPM * CNDM * CNPAM * SNDF * SNDMA * MAMFA
RMAN	Reliability of mouth activation after entering water	CA * NFI * NHI * NII * NINTI * KS * ENV * SNDF * SNDMA * MAWA

<sup>a</sup>The same basic event DA of “Don PFD after entering the water” is used for these two top events because it has not been examined by the industry; however, once PFD donning in water is established, two types of DA events can be introduced and the model updated accordingly.

Table 9 Definition of scenarios for inflatable PFDs

Donning scenarios	Scenario definition used as intermediate events	Corresponding effectiveness
D1	DBWAA * RAA	Full effectiveness (L)
D2	DBWAA * RAA * RPCO	Full effectiveness (L)
D3	DBWAA * RAA * RPCO * RMAO	Full effectiveness (L)
D4	DBWAA * RAA * RPCO * RMAO	Noneffective (F)
D5	DBWBA * DBWAA * RAA	Full effectiveness (L)
D6	DBWBA * DBWAA * RAA * RPCO	Full effectiveness (L)
D7	DBWBA * DBWAA * RAA * RPCO * RMAO	Full effectiveness (L)
D8	DBWBA * DBWAA * RAA * RPCO * RMAO	Noneffective (F)
D9	DBWBA * DBWAA * RAA * DAWI	Full effectiveness (L)
D10	DBWBA * DBWAA * RAA * DAWI	Noneffective (F)
D11	DBWBA * DBWAA * RAA * DAWD * RPCN	Full effectiveness (L)
D12	DBWBA * DBWAA * RAA * DAWD * RPCN * RMAN	Full effectiveness (L)
D13	DBWBA * DBWAA * RAA * DAWD * RPCN * RMAN	Noneffective (F)
D14	DBWBA * DBWAA * RAA * DAWD	Noneffective (F)

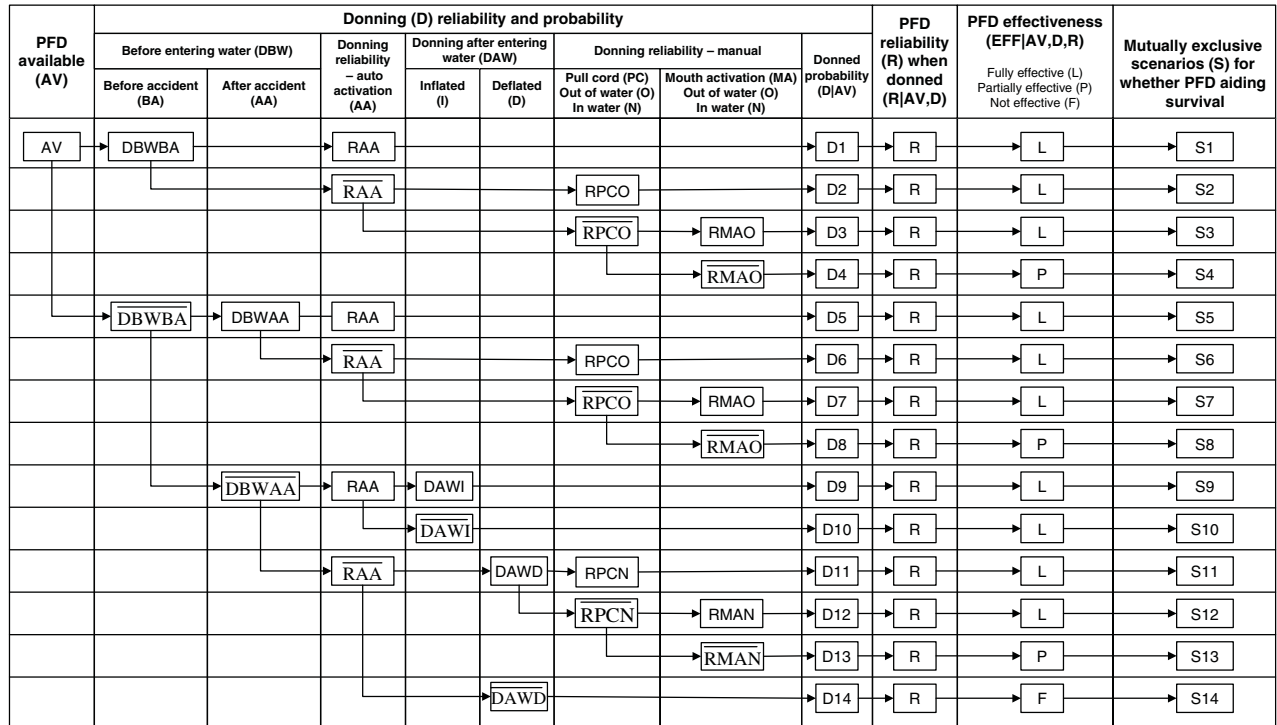


Fig. 7 Probability tree of hybrid PFD success scenarios

Table 10 Definition of events for hybrid PFDs

Top events	Definition	Basic events
DBWBA	PFD donned before entering water before accident	DP * W
DBWAA	PFD donned before entering water after accident	CP * NFO * NH * NIO * NINTO * DP
DAWI <sup>a</sup>	PFD donned after entering water, inflated	NFI * NHI * NII * NINTI * CA * KS * ENV * EDI * DA
DAWD <sup>a</sup>	PFD donned after entering water, deflated	NFI * NHI * NII * NINTI * CA * KS * ENV * EDI * DA
RPCO	Reliability of gas mechanism before entering water by pulling inflation cord	CP * NFO * NH * NIO * NINTO * SNDF * SNDMB *
RMAO	Reliability of mouth activation mechanism before entering water	(CASA + RVF - CASA * RVF) * CLPM * CNDM * CNPAM * MAMF
RAA	Reliability of automatic activation	CP * NFO * NH * NIO * NINTO * SNDF * SNDMB * MAWB
RPCN	Reliability of gas mechanism after entering water by pulling inflation cord	AAF * CLPA * CNDA * CNPAA * SNDF * SNDMB *
RMAN	Reliability of mouth activation after entering water	(CASA + RVF - CASA * RVF)
		CA * NFI * NHI * NII * NINTI * CLPM * CNDAM * CNPM *
		SNDF * SNDMA * MAMFA
		CA * NFI * NHI * NII * NINTI * KS * ENV * SNDF * SNDMA * MAWA

<sup>a</sup>The same basic event DA of “Don PFD after entering the water” is used for these two top events because it has not been examined by the industry; however, once PFD donning in water is established, two types of DA events can be introduced and the model updated accordingly.

Table 11 Definition of scenarios for hybrid PFDs

Donning scenarios	Scenario definition used as intermediate events	Corresponding effectiveness
D1	DBWAA * RAA * EFFL	Full effectiveness (L)
D2	DBWAA * RAA * RPCO * EFFL	Full effectiveness (L)
D3	DBWAA * RAA * RPCO * RMAO * EFFL	Full effectiveness (L)
D4	DBWAA * RAA * RPCO * RMAO * EFFP	Partial effectiveness (P)
D5	DBWBA * DBWAA * RAA * EFFL	Full effectiveness (L)
D6	DBWBA * DBWAA * RAA * RPCO * EFFL	Full effectiveness (L)
D7	DBWBA * DBWAA * RAA * RPCO * RMAO * EFFL	Full effectiveness (L)
D8	DBWBA * DBWAA * RAA * RPCO * RMAO * EFFP	Partial effectiveness (P)
D9	DBWBA * DBWAA * RAA * DAWI * EFFL	Full effectiveness (L)
D10	DBWBA * DBWAA * RAA * DAWI * EFFP	Noneffective (F)
D11	DBWBA * DBWAA * RAA * DAWD * RPCN * EFFL	Full effectiveness (L)
D12	DBWBA * DBWAA * RAA * DAWD * RPCN * RMAN * EFFL	Full effectiveness (L)
D13	DBWBA * DBWAA * RAA * DAWD * RPCN * RMAN * EFFP	Partial effectiveness (P)
D14	DBWBA * DBWAA * RAA * DAWD * EFFP	Noneffective (F)

**Table 12(a) Adult partial and full effectiveness parameter relationships**

Event (symbol) and environments	Primary units [secondary units]	Weight factor	Comments or limitations	Linear model defined by two points: (parameter value, probability) [corresponding secondary units]	
				First point	Second point
Freeboard (FB)	mm [in.]	0.30	Average for all subjects without any negative values	(75, 0.8)	(180, 1)
Open-water (OW) environment				[3, 0.8]	[7, 1]
Freeboard (FB)	mm [in.]	0.30	Average for all subjects without any negative values	(45, 0.8)	(125, 1)
Near-shore (NS) environment				[1.75, 0.8]	[5, 1]
Freeboard (FB)	mm [in.]	0.30	Average for all subjects without any negative values	(25, 0.8)	(115, 1)
Calm-water (CW) environment				[1, 0.8]	[4.5, 1]
Heave period (HP)	s	0.28	Result of a single “demanding” subject tested as detailed in the Appendix	(0.8, 1)	(2.5, 0.5)
Environments: OW and NS					
Turning time and Ability (TT)	s	0.20	Corrected average for all subjects, and all subjects must pass stability per applicable standards	(2, 1)	(7, 0.75)
Environments: OW and NS					
Face plane angle (FPA)	deg	0.10	Average for all subjects	Piecewise linear: (45, 1) (-15, 0.8) (105, 0.8)	Piecewise linear: (45, 1) (-15, 0.8) (105, 0.8)
All environments					
Placement security based on ride-up (PS)	mm [in.]	0.10	Average for all subjects	(25, 1) [1, 1]	(150, 0.75) [6, 0.75]
All environments					
Detectability (DTC)	Not applicable	0.02	Not applicable	See Table 12(b)	See Table 12(b)
All environments <sup>a</sup>					

See Table 12(b) for detectability (DTC) features in all environments.

**Table 12(b) Adult partial and full effectiveness parameter relationships: Detectability (DTC) features in all environments**

Detectability (DTC) features—all environments	Weight factor	Scoring (1 if a feature is provided; 0 if a feature is not provided; 0.5 if a feature is provided but does not meet accepted practices or indeterminate)	Points defining model
Highly visible color	0.2	Multiply the score by the weight factor. Add up the products to obtain a weighted score and multiply by 0.8 to determine the DTC value.	Minimum possible DTC level = 0.0
Retroreflective material	0.2		
Whistle	0.1	Maximum possible DTC level = 0.8	
Light	0.1		
Personal locator beacon (PLB)	0.1		
Distress signal (flares)	0.1		
Signal mirror	0.1		
Dye marker	0.1		

**Table 12(c) Adult limitations on full effectiveness parameter relationships**

Event (symbol) (units)	Open-water (OW) environment	Near-shore (NS) environment	Calm-water (CW) environment	Example restrictions
Freeboard (FB) (mm (in.))	Prob. = 0 for FB < 75 (3) Prob. = 1 for FB > 175 (7) Reject if FB < 75 (3)	Prob. = 0 for FB < 45 (1.75) Prob. = 1 for FB > 125 (5) Reject if FB < 45 (1.75)	Prob. = 0 for FB < 25 (1) Prob. = 1 for FB > 115 (4.5) Reject if FB < 25 (1)	None
Heave period (HP) (s)	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 2.0 Reject if HP > 2.0	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 2.75 Reject if HP > 2.75	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 3.5 Reject if HP > 3.5	None
Turning time and ability (TT) (s)	Prob. = 1 for TT < 2 Prob. = 0 for TT > 9 Reject if TT > 9	Prob. = 1 for TT < 2 Prob. = 0 for TT > 13.5 Reject if TT > 13.5	TT not required; stability must be met per applicable standards	None
Face plane angle (FPA) (deg)		Prob. = 1 for FPA = 45 deg Prob. = 0 for FPA < -15 deg Prob. = 0 for FPA > 105 deg Reject if FPA < -15 deg or reject if FPA > 105 deg		None
Placement security based on ride-up (PS) (mm (in.))	PS not required; water entry must be met	PS not required; water entry must be met	Prob. = 1 for PS < 25 (1) Prob. = 0 for PS > 250 (10) Reject if PS > 250 (10)	None
Detectability (DTC) (NA)	Min. possible DTC level = 0.16 <sup>a</sup> Max. possible DTC level = 0.8 Reject if DTC < 0.16	Min. possible DTC level = 0.16 <sup>a</sup> Max. level = 0.8 Reject if DTC < 0.16	Min. level = 0.0 Max. level = 0.8 No rejection limit	Camouflage PFD for military use <sup>a</sup>

Max. = maximum; Min. = minimum; NA = not applicable; Prob. = probability.

<sup>a</sup>For restricted-use certification, a PFD will receive maximum level or probability = 1 scores for any exempted feature.

**Table 12(d) Adult limitations on partial effectiveness parameter relationships**

Event (symbol) (units)	Open-water (OW) environment	Near-shore (NS) environment	Calm-water (CW) environment	Example restriction limits
Freeboard (FB) (mm (in.))	Prob. = 0 for FB < 40 (1.5) Prob. = 1 for FB > 175 (7) Reject if FB < 40 (1.5)	Prob. = 0 for FB < 22 (0.875) Prob. = 1 for FB > 125 (5) Reject if FB < 22 (0.875)	Prob. = 0 for FB < 12 (0.5) Prob. = 1 for FB > 115 (4.5) Reject if FB < 12 (0.5)	None
Heave period (HP) (s)	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 2.25 Reject if HP > 2.25	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 2.75 Reject if HP > 2.75	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 3.5 Reject if HP > 3.5	None
Turning time and ability (TT) (s)	Prob. = 1 for TT < 2 Prob. = 0 for TT > 10 Reject if TT > 10	Prob. = 1 for TT < 2 Prob. = 0 for TT > 15 Reject if TT > 15	TT not required; stability must be met per applicable standards	None
Face plane angle (FPA) (deg)	Same as full effectiveness			None
Placement security based on ride-up (PS) (mm (in.))	Same as full effectiveness	Same as full effectiveness	Same as full effectiveness	None
Detectability (DTC) (NA)	Same as full effectiveness	Same as full effectiveness	Same as full effectiveness	Camouflage PFD for military use <sup>a</sup>

NA = not applicable; Prob. = probability.

<sup>a</sup>For restricted-use certification, a PFD will receive maximum level or probability = 1 scores for any exempted feature.**Table 13(a) Example child partial and full effectiveness parameter relationships**

Event (symbol) and environments	Primary units (secondary units)	Weight factor	Comments or limitations	Linear model defined by two points: (parameter value, probability) (corresponding secondary units)	
				First point	Second point
Freeboard (FB) Open-water (OW) environment	mm (in.)	0.30	Average for all subjects without any negative values	(75, 0.8) (3, 0.8)	(180, 1) (7, 1)
Freeboard (FB) Near-shore (NS) environment	mm (in.)	0.30	Average for all subjects without any negative values	(45, 0.8) (1.75, 0.8)	(125, 1) (5, 1)
Freeboard (FB) Calm-water (CW) environment	mm (in.)	0.30	Average for all subjects without any negative values	(25, 0.8) (1, 0.8)	(115, 1) (4.5, 1)
Heave period (HP) Environments: OW and NS	s	0.24	A child heave period test does not exist and needs to be developed	(0.8, 1)	(2.5, 0.5)
Turning time and ability (TT) Environments: OW and NS	s	0.24	Corrected average for all subjects	(2, 1)	(7, 0.75)
Face plane angle (FPA) All environments	deg	0.08	Average for all subjects	Piecewise linear: (45, 1) (-15, 0.8) (105, 0.8)	Piecewise linear: (45, 1) (-15, 0.8) (105, 0.8)
Placement security based on ride-up (PS) All environments	mm (in.)	0.10	Average for all subjects	(25, 1) (1, 1)	(150, 0.75) (6, 0.75)
Detectability (DTC) All environments	Not applicable	0.04	Not applicable	See Table 13(b)	See Table 13(b)

See Table 13(b) for detectability (DTC) features in all environments.

**Table 13(b) Example child recommended partial and full effectiveness parameter relationships: Detectability (DTC) features in all environments**

Detectability (DTC) features—all environments	Weight factor	Scoring (1 if a feature is provided; 0 if a feature is not provided; 0.5 if a feature is provided but does not meet accepted practices or indeterminate)	Points defining model
Highly visible color	0.2	Multiply the score by the weight factor. Add up the products to obtain a weighted score and multiply by 0.8 to determine the DTC value.	Minimum possible DTC level = 0.0
Retroreflective material	0.3		Maximum possible DTC level = 0.8
Whistle	0.1		
Light	0.1		
Personal locator beacon (PLB)	0.1		
Distress signal (flares)	0		
Signal mirror	0.1		
Dye marker	0.1		

**Table 13(c) Example child recommended limitations on full effectiveness parameter relationships**

Event (symbol) (units)	Open-water (OW) environment	Near-shore (NS) environment	Calm-water (CW) environment	Example restrictions
Freeboard (FB) (mm (in.))	Prob. = 0 for FB < 75 (3) Prob. = 1 for FB > 175 (7) Reject if FB < 75 (3)	Prob. = 0 for FB < 45 (1.75) Prob. = 1 for FB > 125 (5) Reject if FB < 45 (1.75)	Prob. = 0 for FB < 25 (1) Prob. = 1 for FB > 115 (4.5) Reject if FB < 25 (1)	None
Heave period (HP) (s)	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 2.0 Reject if HP > 2.0	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 2.75 Reject if HP > 2.75	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 3.5 Reject if HP > 3.5	None
Turning time and ability (TT) (s)	Prob. = 1 for TT < 2 Prob. = 0 for TT > 10 Reject if TT > 10	Prob. = 1 for TT < 2 Prob. = 0 for TT > 12 Reject if TT > 12	TT not required; stability must be met per applicable standards	None
Face plane angle (FPA) (deg)		Prob. = 1 for FPA = 45 deg Prob. = 0 for FPA < -15 deg Prob. = 0 for FPA > 105 deg Reject if FPA < -15 deg or reject if FPA > 105 deg		None
Placement security based on ride-up (PS) (mm (in.))	Not required	Not required	Prob. = 1 for PS < 25 (1) Prob. = 0 for PS > 175 (7) Reject if PS > 175 (7)	None
Detectability (DTC) (NA)	Min. level = 0 Max. level = 0.8	Min. level = 0 Max. level = 0.8	Min. level = 0 Max. level = 0.8	None

Max. = maximum; Min. = minimum; NA = not applicable; Prob. = probability.

**Table 13(d) Example child recommended limitations on partial effectiveness parameter relationships**

Event (symbol) (units)	Open-water (OW) environment	Near-shore (NS) environment	Calm-water (CW) environment	Example restriction limits
Freeboard (FB) (mm (in.))	Prob. = 0 for FB < 40 (1.5) Prob. = 1 for FB > 175 (7) Reject if FB < 40 (1.5)	Prob. = 0 for FB < 22 (0.875) Prob. = 1 for FB > 125 (5) Reject if FB < 22 [0.875]	Prob. = 0 for FB < 12 (0.5) Prob. = 1 for FB > 115 (4.5) Reject if FB < 12 (0.5)	None
Heave period (HP) (s)	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 2.25 Reject if HP > 2.25	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 2.75 Reject if HP > 2.75	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 3.5 Reject if HP > 3.5	None
Turning time and ability (TT) (s)	Prob. = 1 for TT < 2 Prob. = 0 for TT > 10 Reject if TT > 10	Prob. = 1 for TT < 2 Prob. = 0 for TT > 15 Reject if TT > 15	TT not required; stability must be met per applicable standards	None
Face plane angle (FPA) (deg)	Same as full effectiveness			None
Placement security based on ride-up (PS) (mm (in.))	Same as full effectiveness	Same as full effectiveness	Prob. = 1 for PS < 25 (1) Prob. = 0 for PS > 185 (7.5) Reject if PS > 185 (7.5)	None
Detectability (DTC) (NA)	Same as full effectiveness	Same as full effectiveness	Same as full effectiveness	None

NA = not applicable; Prob. = probability.

in USCG-approved and certified laboratories, such as UL. In the United States, wearable PFDs are classified into types according to their performance as provided in Table 2. The primary principle behind the performance of a PFD is to provide sufficient buoyancy and distribution so that a device's center of buoyancy with respect to the center of gravity of a wearer brings the head and torso to favorable angles, and the airways are brought above the water surface to provide a minimum clearance. The buoyancy distribution and amount may provide turning tendency for most or at least some unconscious users to stay face up for PFD Types I and II, respectively. The PFD must be secured to the user in a manner that allows it to maintain the performance desired. There are many other performance requirements imposed on these PFDs that cover strength, reliability, quality, durability, etc.

Personal flotation devices provide buoyancy according to one of the following means:

- Inherently buoyant PFDs that are constructed by using buoyant foam material and provide buoyancy without the need for inflation. They are puncture proof, and the buoyant elements are unsinkable.
- Inflatable PFDs that feature a chamber inflated by gas when buoyancy is needed. Manual and automatic options are available.
- Hybrid PFDs that feature an inflatable chamber and inherently buoyant material.

### 3 Performance Quantification and Aggregation

**3.1 A Generalized Structure for Performance Models.** The origins of performance measurement of PFDs was initially structured by what was termed the lifesaving index (LSI), which defined the relationship between four factors that are necessary for a PFD to provide lifesaving assistance—effectiveness, reliability, availability, and wearability. In the PFDRRA models, these four variables are defined in the context of measurement as follows:

- Effectiveness (EFF)—Probability that the PFD provides adequate support/airway protection for user to avoid drowning.

The water conditions (sea state) in which the user needs support affects this probability.

- Reliability (R). Probability that the PFD provides its designed effectiveness during a marine event. The durability, toughness, resistance to environmental stressors such as weathering, and simplicity are the primary factors that affect this probability.
- Availability (AV). Probability that the PFD can be accessed by the user during a marine event. The style or USCG type of PFD or PFDs that the user has provided on the watercraft or facility and the utility and aesthetics of the PFD design affect this probability. If the PFD is worn, AV = 1 by definition.
- Wearability (W). Probability that the PFD is worn during a marine event. The utility, comfort, and aesthetics of the design as well as subjective judgment of PFD users affect this probability.

The PFDRRA models consist of three computational procedures for inherently buoyant, inflatable, and hybrid (i.e., combined inherent and inflatable buoyancy) PFDs that aggregate the performance of PFDs on the basis of selected test results for effectiveness, reliability, donning, and use with limits for individual performance test

results. The underlying factors affecting performance are categorized as follows: (1) design factors relating to PFD in-water effectiveness in various environments; (2) factors relating to PFD design reliability, such as buoyancy method, strength, and inflation mechanism; (3) design wearability, such as comfort and utility; and (4) factors relating to PFD users. The models are applicable to the three buoyancy methods of inherently buoyant, inflatable, and hybrid PFDs, and three environments as provided in Fig. 3: (1) open-water (OW) environment that corresponds to ISO life jacket level 150–275 N environment as examples, (2) near-shore (NS) environment that corresponds to ISO life jacket level 100 N environment as an example, and (3) calm-water (CW) and conscious-user environments that correspond to ISO buoyancy aid level 50 N environment as an example. Also, PFDs approved with clearly stated restrictions can be handled by the models by allowing performance factor values to be adjusted commensurate with the restrictions, e.g., user training and acceptance of the need for manual inflation in place of automatic inflation, as long as the aggregate performance can be demonstrated to meet or exceed the aggregate performance of other similar devices. This paper provides the procedures for determining in-water effectiveness on the aggregate and the procedures for computing the probability of a device saving lives.

**Table 14(a) Example infant recommended partial and full effectiveness parameter relationships**

Event (symbol) and environments	Primary units (secondary units)	Weight factor	Comments or limitations	Linear model defined by two points: (parameter value, probability) (corresponding secondary units)	
				First point	Second point
Freeboard (FB)	mm (in.)	0.30	Average for all subjects without any negative values	(75, 0.8) (3, 0.8)	(180, 1) (7, 1)
Open-water (OW) environment					
Freeboard (FB)	mm (in.)	0.30	Average for all subjects without any negative values	(45, 0.8) (1.75, 0.8)	(125, 1) (5, 1)
Near-shore (NS) environment					
Freeboard (FB)	mm (in.)	0.35	Average for all subjects without any negative values	(25, 0.8) (1, 0.8)	(115, 1) (4.5, 1)
Calm-water (CW) environment					
Heave period (HP)	s	0.25	An infant heave period test does not exist and needs to be developed.	(0.8, 1)	(2.5, 0.5)
Environments: OW and NS					
Turning time and ability (TT)	s	0.25	Corrected average for all subjects	(2, 1)	(7, 0.75)
Environments: OW and NS					
Face plane angle (FPA)	deg	0.05	Average for all subjects	Crotch strap (1)	Crotch strap (1)
All environments		(except CW use 0)		No crotch strap (0)	No crotch strap (0)
Placement security based on ride-up (PS)	mm (in.)	0.10	A ride-up test does not apply. Infant devices are required to have a crotch strap.	(25, 1) (1, 1)	(150, 0.75) (6, 0.75)
All environments					
Detectability (DTC)	Not applicable	0.05	Not applicable	See Table 14(b)	See Table 14(b)
All environments					

See Table 14(b) for detectability (DTC) features in all environments.

**Table 14(b) Example infant recommended partial and full effectiveness parameter relationships: Detectability (DTC) features in all environments**

Detectability (DTC) features—all environments	Weight factor	Scoring (1 if a feature is provided; 0 if a feature is not provided; 0.5 if a feature is provided but does not meet accepted practices or indeterminate)	Points defining model
Highly visible color	0.35	Multiply the score by the weight factor. Add up the products to obtain a weighted score and multiply by 0.8 to determine the DTC value.	Minimum possible DTC level = 0.0
Retroreflective material	0.3		
Whistle	0		Maximum possible DTC level = 0.8
Light	0.15		
Personal locator beacon (PLB)	0.1		
Distress signal (flares)	0		
Signal mirror	0		
Dye marker	0.1		

**Table 14(c) Example infant recommended limitations on full effectiveness parameter relationships**

Event (symbol) (units)	Open-water (OW) environment	Near-shore (NS) environment	Calm-water (CW) environment	Example restrictions
Freeboard (FB) (mm (in.))	Prob. = 0 for FB < 75 (3) Prob. = 1 for FB > 175 (7) Reject if FB < 75 (3)	Prob. = 0 for FB < 45 (1.75) Prob. = 1 for FB > 125 (5) Reject if FB < 45 (1.75)	Prob. = 0 for FB < 25 (1) Prob. = 1 for FB > 115 (4.5) Reject if FB < 25 (1)	None
Heave period (HP) (s)	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 2.0 Reject if HP > 2.0	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 2.75 Reject if HP > 2.75	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 3.5 Reject if HP > 3.5	None
Turning time and ability (TT) <sup>a</sup> (s)	Prob. = 1 for TT < 2 Prob. = 0 for TT > 7.5 Reject if TT > 7.5	Prob. = 1 for TT < 2 Prob. = 0 for TT > 9.5 Reject if TT > 9.5	TT not required; stability must be met per applicable standards	None
Face plane angle (FPA) (deg)		Prob. = 1 for FPA = 45 deg Prob. = 1 for FPA < -15 deg Prob. = 0 for FPA > 105 deg Reject if FPA < -15 deg or reject if FPA > 105 deg		None
Placement security based on ride-up (PS) (mm (in.))	Not required	Not required A ride-up test does not apply. Infant devices are required to have a crotch strap.	Crotch strap (1) No crotch strap (0)	None
Detectability (DTC) (NA)	Min. level = 0 Max. level = 0.8	Min. level = 0 Max. level = 0.8	Min. level = 0 Max. level = 0.8	None

Max. = maximum; Min. = minimum; NA = not applicable; Prob. = probability.

<sup>a</sup>Turning time ability is required for all environments.

**Table 14(d) Example infant recommended limitations on partial effectiveness parameter relationships**

Event (symbol) (units)	Open water (OW) environment	Near-shore (NS) environment	Calm-water (CW) environment	Example restriction limits
Freeboard (FB) (mm (in.))	Prob. = 0 for FB < 40 (1.5) Prob. = 1 for FB > 175 (7) Reject if FB < 40 (1.5)	Prob. = 0 for FB < 22 (0.875) Prob. = 1 for FB > 125 (5) Reject if FB < 22 (0.875)	Prob. = 0 for FB < 12 (0.5) Prob. = 1 for FB > 115 (4.5) Reject if FB < 12 (0.5)	None
Heave period (HP) (s)	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 2.25 Reject if HP > 2.25	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 2.75 Reject if HP > 2.75	Prob. = 1 for HP < 0.8 Prob. = 0 for HP > 3 Reject if HP > 3	None
Turning time and ability (TT) <sup>a</sup> (s)	Prob. = 1 for TT < 2 Prob. = 0 for TT > 10 Reject if TT > 10	Prob. = 1 for TT < 2 Prob. = 0 for TT > 13.5 Reject if TT > 13.5	TT not required; stability must be met per applicable standards	None
Face plane angle (FPA) (deg)	Same as full effectiveness			None
Placement security based on ride-up (PS) (mm (in.))	Same as full effectiveness	Same as full effectiveness A ride-up test does not apply. Infant devices are required to have a crotch strap.	Crotch strap (1) No crotch strap (0)	None
Detectability (DTC) (not applicable)	Same as full effectiveness	Same as full effectiveness	Same as full effectiveness	None

<sup>a</sup>Turning time ability is required for all environments.

The performance of a PFD according to these models depends on four primary events as shown in Fig. 4: (1) PFD is available; (2) PFD is being properly donned; (3) PFD is reliable; and (4) PFD is effective. The models allow for partially meeting the conditions such as holding on to the PFD instead of properly donning it. PFD effectiveness as used in the PFDRA models means its ability to provide a safe flotation attitude and is quantified as the probability that the PFD is effective given the conditions that the PFD is donned and reliable. Effectiveness is affected and defined by the parameters provided in Table 3. Tables 4(a,b) and 5 list the performance reliability and availability parameters and their definitions. Table 5 summarizes parameters relating to PFD users that are applicable to all buoyancy methods and environments.

**3.2 Inherently Buoyant Devices.** The performance of a PFD depends on four primary events as shown in Fig. 4. Because of dependencies among these events, a probability tree of success

scenarios is used as shown in Fig. 5 with events defined in Table 6, in which the joint occurrence of events, i.e., intersection ( $\cap$ ), is denoted by using the symbol \*. Therefore, the performance success probability  $P(S)$  of an inherently buoyant PFD can be computed as

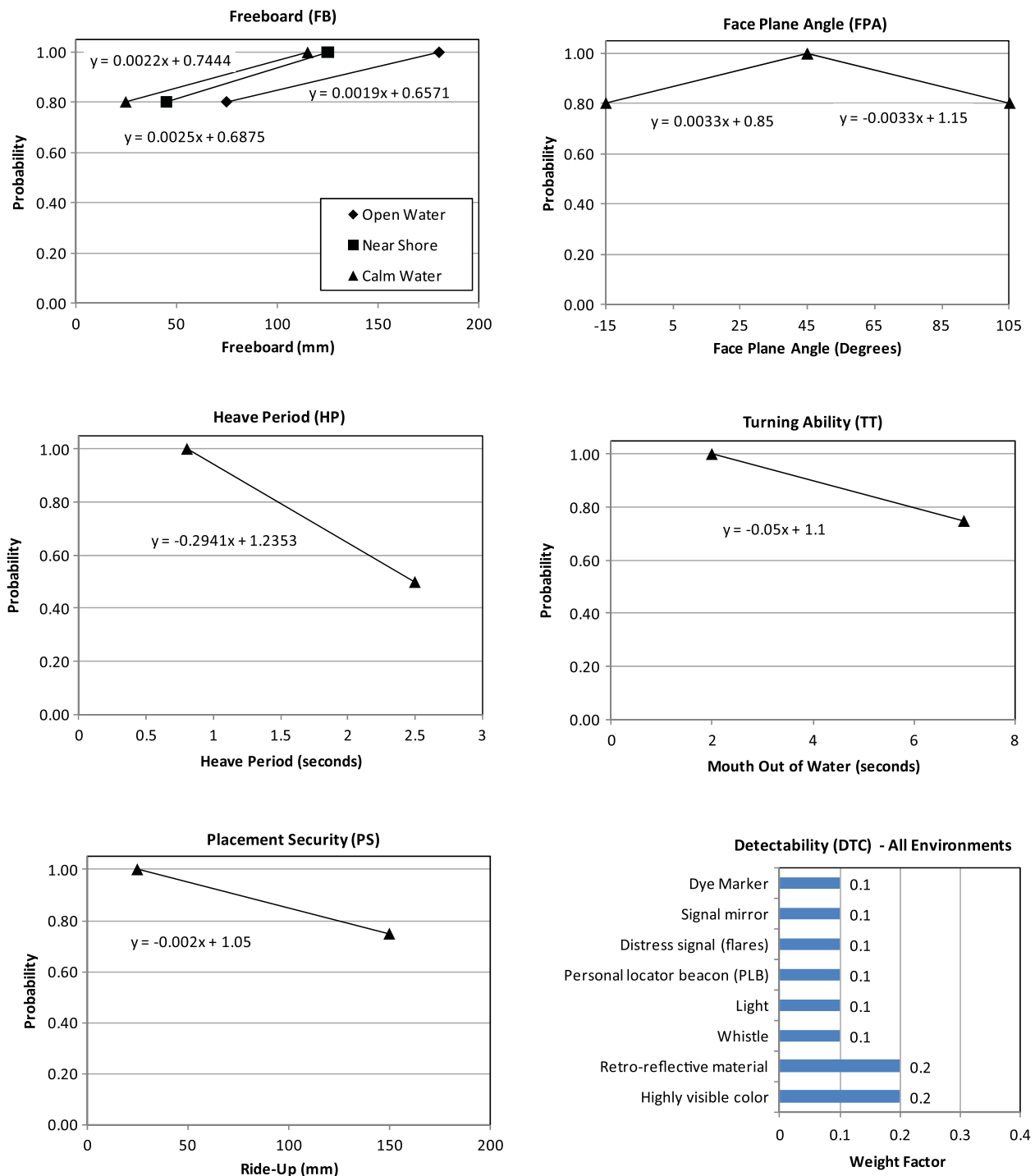
$$P(S) = P(AV) P(D|AV) P(R|AV, D) P(EFF|AV, D, R) \quad (1)$$

where

- $P(AV)$  = probability that the PFD is available when needed.
- $P(D|AV)$  = probability that the PFD is properly donned given it is available, or  $P(D1 \cup D2 \cup D3)$ .
- $P(R|AV, D)$  = probability that the PFD is reliable given that it is properly donned and available, or  $P(BME \cap PMB \cap ROC \cap SNDF \cap SNDMB)$ .
- $P(EFF|AV, D, R)$  = probability that the PFD is effective given that it is available, properly donned, and reliable. This value is determined as the weighted sum of performance

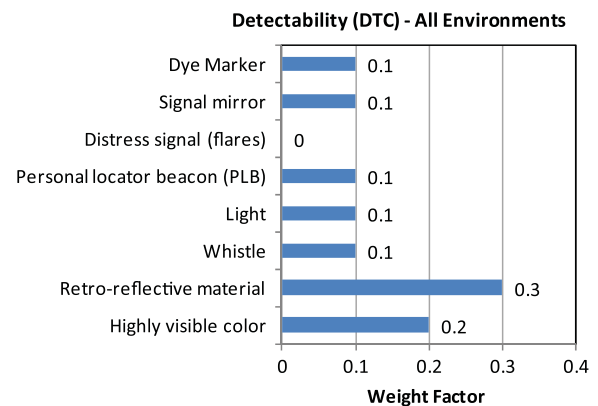
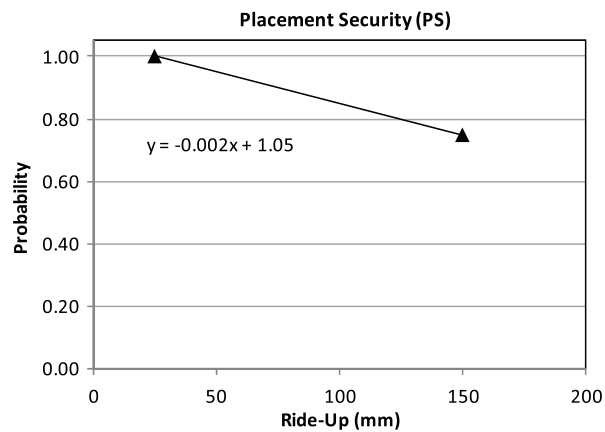
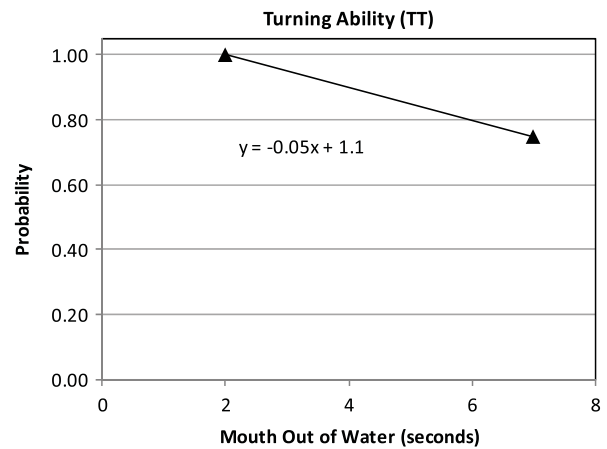
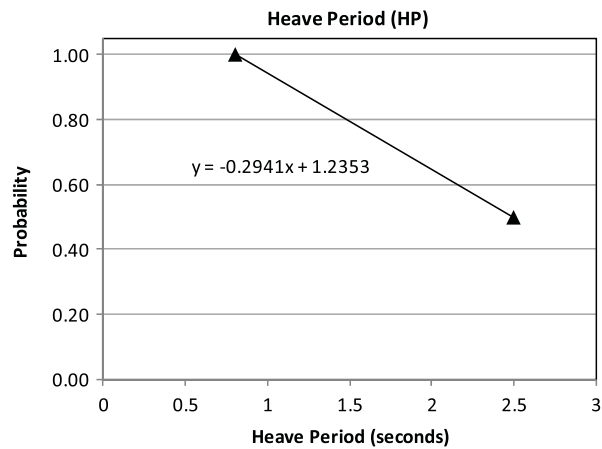
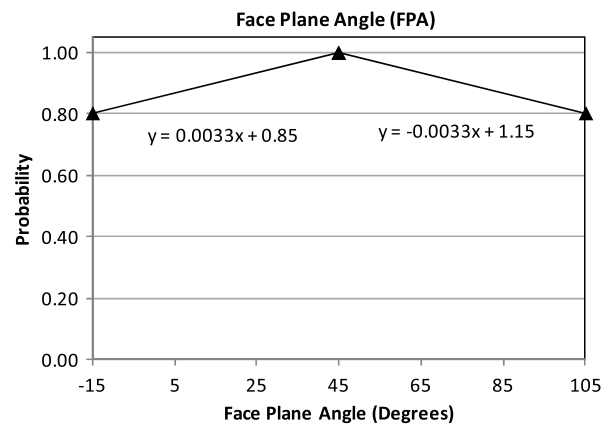
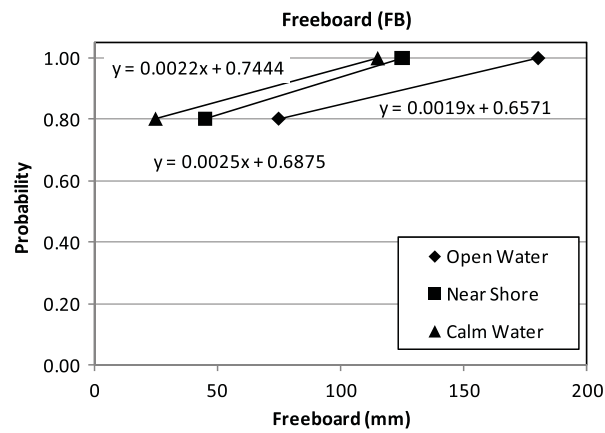
measures of freeboard, face plane angle, heave period, turning ability, placement security, and detectability, i.e.,  $0.30\text{FB} + 0.28\text{HP} + 0.20\text{TT} + 0.10\text{FPA} + 0.10\text{PS} + 0.02\text{DTC}$  using weight factors as determined from expert elicitation of 0.30, 0.28, 0.20, 0.10, 0.10, and 0.02.

Table 7 defines the events related to PFD being properly donned. The basic events and parameters used in Eq. (1) are defined in subsequent paragraphs. The probabilities of events and parameters relating to respective PFD tests along with suggested default values are provided in subsequent paragraphs.



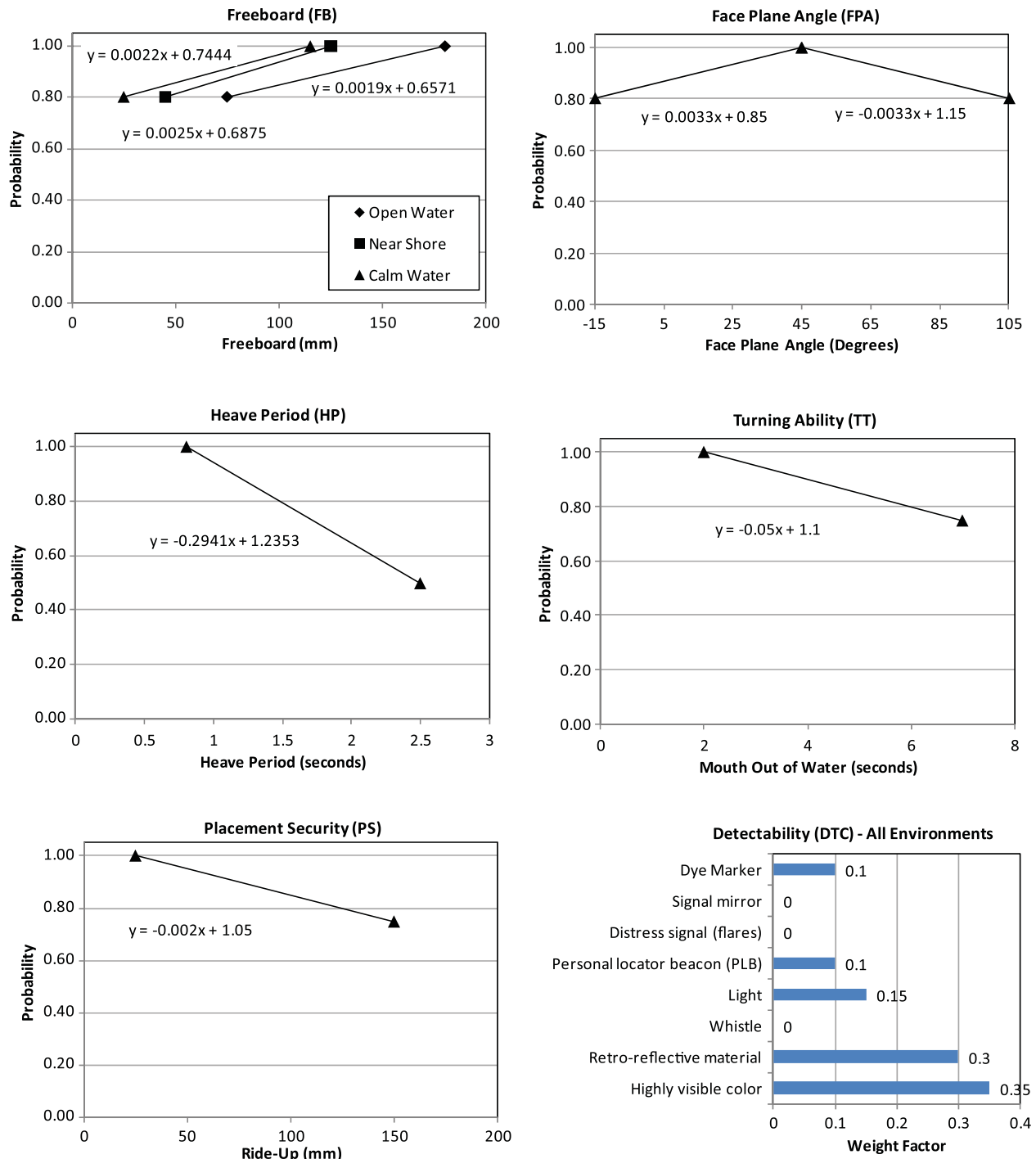
(a)

Fig. 8 (a) Illustrative PFD performance effectiveness relationships for adults, (b) Illustrative PFD Performance effectiveness relationships for children, and (c) Illustrative PFD performance effectiveness relationships for infants



(b)

Fig. 8 (Continued.)



(c)

Fig. 8 (Continued.)

**3.3 Inflatable Devices.** The performance of a PFD in this case also depends on four primary events as shown in Fig. 4. Because of dependencies among these events, a probability tree of success scenarios is used as shown in Fig. 6 and Table 8. The performance success probability  $P(S)$  of a PFD can be computed by using Eq. (1) where in this case

- $P(AV)$  = probability that the PFD is available when needed.

- $P(D|AV)$  = probability that the PFD is properly donned given it is available, or  $P(D1 \cup D2 \cup D3 \cup D5 \cup D6 \cup D7 \cup D9 \cup D11 \cup D12)$ .
- $P(R|AV, D)$  = probability that the PFD is reliable given that it is properly donned and available, or  $P(BME \cap PMB \cap ROC \cap SNDF \cap SNDMB)$ .
- $P(EFF|AV, D, R)$  = probability that the PFD is effective given that it is available, properly donned, and reliable. This

**Table 15(a) Recommended event relationships for inherently buoyant PFD designs**

Event (symbol) and environments	Primary units (secondary units)	Comments or limitations	Linear model defined by two points: (parameter value, probability) (corresponding secondary units)	
			First point	Second point
Buoyant material effective (BME) Open-water (OW) environment	N (lb)	Average value	(70, 0.7) (15.5, 0.7)	(100, 0.95) (22.0, 0.95)
Buoyant material effective (BME) Near-shore (NS) environment	N (lb)	Average value	(50, 0.7) (11.0, 0.7)	(85, 0.95) (18.5, 0.95)
Buoyant material effective (BME) Calm-water (CW) environment	N (lb)	Average value	(35, 0.7) (7.5, 0.7)	(70, 0.95) (15.5, 0.95)
Don PFD before entering the water (DP) All environments	s	Average value	(15, 1)	(60, 0.80)
Don PFD after entering the water (DA) All environments	s	Average value	(15, 1)	(60, 0.80)
PFD maintains buoyancy (PMB) All environments	Not applicable	Average value	Probability = 1, if buoyant materials meet applicable standards; otherwise 0	
Shell not defective (SNDF) All environments	Not applicable	Average value	Probability = 0.999 if PFD passes applicable standards	
Shell not defective before entering water (SNDMB) All environments	Not applicable	Average value	Probability = 0.999 if PFD passes applicable standards	
Shell not damaged after entering water (SNDMA) All environments	Not applicable	Average value	Probability = 0.999, if PFD passes applicable standards, such as the UL 1123 dynamic strength test	
Other components vital to providing buoyancy operate (ROC) All environments	Not applicable	Average value	Probability = 0.999	
Wearability (W) All environments	Not applicable	See Tables 15(b-c)		

**Table 15(b) Adult wearability factors**

Wearability (W) factors	Weight factor for open-water environment	Weight factor for near-shore environment	Weight factor for calm-water environment	Score in the range [0,1] in meeting the intent of each factor	Points defining model
Range of motion	0.2	0.2	0.25	Multiply the score by the weight factor. Add up the products to obtain a weighted score to obtain W as follows: Open-water environment: $W = 0.1 + (\text{weighted score})0.40$ Near-shore environment: $W = 0.1 + (\text{weighted score})0.45$	Open-water environment: min. possible $W = 0.1$ ; max. possible $W = 0.5$
Seating comfort	0.1	0.1	0.1		
Appearance and color	0.1	0.1	0.1	Open-water environment: $W = 0.1 + (\text{weighted score})0.40$ Near-shore environment: $W = 0.1 + (\text{weighted score})0.45$	Near-shore environment: min. possible $W = 0.1$ ; max. possible $W = 0.55$
Perceived comfort: breathable shell, mesh shoulders, side panels	0.15	0.15	0.1		
Actual comfort: breathable shell, mesh shoulders, side panels	0.2	0.2	0.2	Calm-water environment: $W = 0.1 + (\text{weighted score})0.7$	Calm-water environment: min. possible $W = 0.1$ ; max. possible $W = 0.8$
Amount of body coverage	0	0	0		
Appropriateness for activity/ appropriateness for accepted user practice	0.1	0.1	0.1		
Stiffness/flexibility	0	0	0		
Bulkiness	0.15	0.15	0.15		

Max. = maximum; Min. = minimum.

value is determined as the weighted sum of performance measures of freeboard, face plane angle, heave period, turning ability, placement security, and detectability, e.g., in the case of inherently buoyant PFDs, the weighted sum can be computed as  $0.30\text{FB} + 0.28\text{HP} + 0.20\text{TT} + 0.10\text{FPA} + 0.10\text{PS} + 0.02\text{DTC}$  using weight factors as determined from expert elicitation of 0.30, 0.28, 0.20, 0.10, 0.10, and 0.02.

Table 9 defines the events related to PFD being properly donned. The basic events and parameters used in Eq. (1) are defined in subsequent paragraphs. The probabilities of events and parameters are provided or related to respective PFD tests in subsequent paragraphs along with suggested default values.

**3.4 Hybrid Devices.** The performance of a PFD in this case also depends on four primary events as shown in Fig. 4. Because of

dependencies among these events, a probability tree of success scenarios is used as shown in Fig. 7 and Table 10. The performance success probability  $P(S)$  of a PFD can be computed by using Eq. (1) where for hybrid devices, two cases of effectiveness, full and partial, are considered as follows:

- $P(AV)$  = probability that the PFD is available when needed.
- $P(D|AV)$  = probability that the PFD is used with full buoyancy (inflated) given it is available, or  $P(D1 \cup D2 \cup D3 \cup D5 \cup D6 \cup D7 \cup D9 \cup D11 \cup D12)$ .
- $P(R|AV, D)$  = probability that the PFD is reliable given that it is donned and available, or  $P(BME \cap PMB \cap ROC \cap SNDF \cap SNDMB)$ .
- $P(EFFL|AV, D, R)$  = probability that the PFD is properly effective given that it is available, donned, and reliable when PFD is used with full buoyancy (inflated). This value is determined as the weighted sum of performance measures of

**Table 15(c) Example child wearability factors**

Wearability (W) factors <sup>a</sup>	Weight factor for open-water environment	Weight factor for near shore environment	Weight factor for calm-water environment	Score in the range [0,1] in meeting the intent of each factor	Points defining model
Range of motion	0.2	0.2	0.3	Multiply the score by the weight factor. Add up the products to obtain a weighted score to obtain W as follows: Open-water environment: $W = 0.1 + (\text{weighted score})0.50$ Near-shore environment: $W = 0.1 + (\text{weighted score})0.6$	Open-water environment: min. possible $W = 0.1$ ; max. possible $W = 0.6$
Seating comfort	0.1	0.1	0.1		
Appearance and color	0.2	0.2	0.2		
Perceived comfort: breathable shell, mesh shoulders, side panels	0.15	0.15	0.15	Calm-water environment: $W = 0.1 + (\text{weighted score})0.7$	Near-shore environment: min. possible $W = 0.1$ ; max. possible $W = 0.7$
Actual comfort: breathable shell, mesh shoulders, side panels	0.15	0.15	0.15		
Amount of body coverage	0	0	0		
Appropriateness for activity/ appropriateness for accepted user practice	0.1	0.1	0.1		Calm-water environment: min. possible $W = 0.1$ ; max. possible $W = 0.8$
Stiffness/flexibility	0	0	0		
Bulkiness	0.1	0.1	0.1		

Max. = maximum; Min. = minimum.

<sup>a</sup>Factors with zero weight factors are retained for consistency in presentations across users (i.e., adult, child, and infant).

**Table 15(d) Example infant wearability factors**

Wearability (W) factors	Weight factor for open-water environment	Weight factor for near-shore environment	Weight factor for calm-water environment	Score in the range [0,1] in meeting the intent of each factor	Points defining model
Range of motion	0.15	0.15	0.15	Multiply the score by the weight factor. Add up the products to obtain a weighted score to obtain W as follows: Open-water environment: $W = 0.10.1 + (\text{weighted score})0.65$ Near-shore Environment: $W = 0.1 + (\text{weighted score})0.65$	Open-water environment: min. possible $W = 0.10.1$ ; max. possible $W = 0.75$
Seating comfort	0.1	0.1	0.1		
Appearance and color	0.2	0.2	0.2		
Perceived comfort: breathable shell, mesh shoulders, side panels	0.2	0.2	0.2	Calm-water environment: $W = 0.1 + (\text{weighted score})0.7$	Near-shore environment: min. possible $W = 0.1$ ; max. possible $W = 0.75$
Actual comfort: breathable shell, mesh shoulders, side panels	0.25	0.25	0.25		
Amount of body coverage	0	0	0		
Appropriateness for activity/ appropriateness for accepted user practice	0	0	0		Calm-water environment: min. possible $W = 0.1$ ; max. possible $W = 0.8$
Stiffness/flexibility	0	0	0		
Bulkiness	0.1	0.1	0.1		

Max. = maximum; Min. = minimum.

freeboard, face plane angle, heave period, turning ability, placement security, and detectability.

- $P(\text{EFP}|\text{AV}, \text{D}, \text{R})$  = probability that the PFD is partially effective given that it is available, donned, and reliable when PFD is used with partial buoyancy (uninflated). This value is also determined as the weighted sum of performance measures of corresponding partial values of freeboard, face plane angle, heave period, turning ability, placement security, and detectability.

Table 11 defines the events related to PFD being properly donned. The basic events and parameters used in Eq. (1) are defined in subsequent paragraphs. The probabilities of events and parameters are provided or related to respective PFD tests in subsequent paragraphs along with suggested default values.

#### 4 Effectiveness and Performance Probabilities

Tables 12(a–d) summarize the full and partial adult PFD performance effectiveness results and limits on PFD performance for all

buoyancy methods and environments. These tables include rejection and restriction limits. The restriction limits are applicable only to PFDs with restrictions on the use of the device, whereas the rejection limits assign a probability of zero to the corresponding event or parameter, which in turn forbids certification of the design for these cases. For child and infant PFDs, the values in Tables 13(a–d), and Tables 14(a–d), respectively, should be used.

Figure 8(a–c) shows PFD performance-effectiveness relationships for freeboard, heave period, turning time and ability, face plane angle, placement security based on ride-up, and detectability for the purpose of illustration, using the respective values for adults, children, and infants as examples. The values provided for children and infants are preliminary illustrative values, and they should be adopted with additional examination and testing.

Tables 15(a–e) summarize the PFD event probabilities and restrictions for inherently buoyant devices and all environments. Tables 16(a–c) summarize those for inflatable and hybrid devices and all environments. Tables 17(a–c) summarizes the PFD user probability results for adults, children, and infants, respectively. Default values (DF) are provided for use in case of missing data for a PFD, beta testing, and analysis, or in cases where the parameters

**Table 15(e) Recommended limitations on event relationships for inherently buoyant PFD designs**

Event (symbol) (units)	Open-water (OW) environment	Near-shore (NS) environment	Calm-water (CW) environment	Example restrictions
Buoyant material effective (BME) (N (lb))	Prob. = 0 for BME < 70 (15.5) Prob. = 1 for BME > 105 (23.3) DF = 70 (15.5)	Prob. = 0 for BME < 50 (11.5) Prob. = 1 for BME > 91 (20.0) DF = 50 (11.0)	Prob. = 0 for BME < 35 (7.5) Prob. = 1 for BME > 78 (17.1) DF = 35 (7.5)	None
Don PFD before entering the water (DP) (s)	Prob. = 1 for DP < 15 Prob. = 0 for DP > 120 DF = 20	Prob. = 1 for DP < 15 Prob. = 0 for DP > 120 DF = 20	Prob. = 1 for DP < 15 Prob. = 0 for DP > 120 DF = 20	Conditional upon being worn
Don PFD after entering the water (DA) (s)	Prob. = 0.88 for DA < 42 Prob. = 0 for DA > 240 DF = 90	Prob. = 0.88 for DA < 42 Prob. = 0 for DA > 240 DF = 90	Prob. = 0.88 for DA < 42 Prob. = 0 for DA > 240 DF = 90	None
PFD maintains buoyancy (PMB)	Probability = 0, if buoyant materials does not meet applicable standard requirements DF = 1			None
Shell not defective (SNDF)		DF = 0.999		None
Shell not defective before entering water (SNDMB)		DF = 0.999		None
Shell not damaged after entering water (SNDMA)	DF = 0.999, if PFD passes applicable standard requirements, such as the ISO dynamic strength test			None
Other components vital to providing buoyancy operate (ROC)		DF = 0.999		None
Wearability (W)		See Tables 15(b–c)		None

DF = default value; Prob. = probability.

**Table 16(a) Recommended event relationships for inflatable and hybrid PFD designs for all environments**

Event (symbol) and environments	Two points: intercept, slope	Limitations	Linear model and points defining model
Automatic activation functions (AAF) All environments, for both INF and HYB	1.075, −0.0375	Average value	$2 s < x < 10 s$ 2(1), 10(0.7)
Gas does not exceed the burst pressure for compartment (CASA) All environments, for both INF and HYB	NA	Average value	Probability = 1, if device meet ISO requirements; otherwise 0 Use default value in Table 16(b)
Cylinder properly loaded (auto-inflation) (CLPA) All environments, for both INF and HYB	NA	NA	Use default value in Table 16(b)
Cylinder properly loaded (manual) (CLPM) All environments, for both INF and HYB	NA	NA	Use default value in Table 16(b)
Cylinder not defective (auto-inflation) (CNDA) All environments, for both INF and HYB	NA	NA	Use default value in Table 16(b)
Cylinder not defective (manual) (CNDM) All environments, for both INF and HYB	NA	NA	Use default value in Table 16(b)
Cylinder not previously activated (auto-inflation) (CNPAA) All environments, for both INF and HYB	NA	NA	Use default value in Table 16(b)
Cylinder not previously activated (manual) (CNPAM) All environments, for both INF and HYB	NA	NA	Use default value in Table 16(b)
Relief valve functions (RVF) All environments, for both INF and HYB	NA	NA	Use default value in Table 16(b)
Manual activation mechanism functions before entering the water (MAMF) All environments, for INF	1.0667, −0.0133	Average value	$5 s < x < 20 s$ 5(1), 20(0.8)
Manual activation mechanism functions before entering the water (MAMF) All environments, for HYB	1.0333, −0.0067	Average value	$5 s < x < 20 s$ 5(1), 20(0.9)
Manual activation mechanism functions after entering the water (MAMFA) All environments, for INF	1.15, −0.03	Average value	$5 s < x < 20 s$ 5(1), 15(0.7)
Manual activation mechanism functions after entering the water (MAMFA) All environments, for HYB	1.3, −0.02	Average value	$15 s < x < 30 s$ 15(1), 30(0.7)
Mouth activation functions using oral inflator (after entering the water) (MAWA) All environments, for INF	1.1714, −0.0114	Average value	$15 s < x < 50 s$ 15(1), 50(0.6)
Mouth activation functions using oral inflator (after entering the water) (MAWA) All environments, for HYB	1.0769, −0.0031	Average value	$25 s < x < 90 s$ 25(1), 90(0.8)
Mouth activation functions using oral inflator (before entering the water) (MAWB) All environments, for INF	1.125, −0.0063	Average value	$20 s < x < 60 s$ 20(1), 60(0.75)
Mouth activation functions using oral inflator (before entering water) (MAWB) All environments, for HYB	1.1, −0.0033	Average value	$30 s < x < 90 s$ 30(1), 90(0.8)

HYB = hybrid; INF = inflatable; NA = not applicable.

**Table 16(b) Recommended limitations on event relationships for inflatable and hybrid PFD designs**

Event (symbol)	All environments (open water (OW), near shore (NS), and calm water (CW))	Example restrictions
Automatic activation functions (AAF)	Prob. = 1 for AFF < 2; Prob. = 0 for AFF > 10; DF = 8	None
Gas does not exceed the burst pressure for compartment (CASA)	Probability = 0, if device does not meet applicable standard requirements; DF = 1	None
Cylinder properly loaded (auto-inflation) (CLPA)	DF = 0.97 with required seal indicator; DF = 0.82 for devices with restrictions and without indicator; DF = 0.97 for devices with restrictions and with indicator	None
Cylinder properly loaded (manual) (CLPM)	DF = 0.97 with required seal indicator; DF = 0.82 for devices with restrictions and without indicator; DF = 0.97 for devices with restrictions and with indicator	None
Cylinder not defective (auto-inflation) (CNDA)	DF = 0.9999	None
Cylinder not defective (manual) (CNDM)	DF = 0.9999	None
Cylinder not previously activated (auto-inflation) (CNPA)	DF = 0.97 with required seal indicator; DF = 0.82 for devices with restrictions and without indicator; DF = 0.97 for devices with restrictions and with indicator	None
Cylinder not previously activated (manual) (CNPAM)	DF = 0.97 with required seal indicator; DF = 0.82 for devices with restrictions and without indicator; DF = 0.97 for devices with restrictions and with indicator	None
Relief valve functions (RVF)	DF = 0.99	None
Manual activation mechanism functions before entering the water (MAMF), for INF	Prob. = 1 for MAMF < 5; Prob. = 0 for MAMF > 20; DF = 15	None
Manual activation mechanism functions before entering the water (MAMF), for HYB	Prob. = 1 for MAMF < 5; Prob. = 0 for MAMF > 30; DF = 15	None

HYB = hybrid; INF = inflatable; DF = default value; Prob. = probability.

**Table 16(c) Recommended limitations on event relationships for inflatable and hybrid PFD designs**

Event (symbol)	Open-water (OW) environment	Near-shore (NS) environment	Calm-water (CW) environment	Example restrictions
Manual activation mechanism functions after entering the water (MAMFA), for INF	Prob. = 1 for MAMFA < 5; Prob. = 0 for MAMFA > 20; DF = 15	Prob. = 1 for MAMFA < 5; Prob. = 0 for MAMFA > 25; DF = 15	Prob. = 1 for MAMFA < 5; Prob. = 0 for MAMFA > 25; DF = 15	None
Manual activation mechanism functions after entering the water (MAMFA), for HYB	Prob. = 1 for MAMFA < 15; Prob. = 0 for MAMFA > 30; DF = 15	Prob. = 1 for MAMFA < 15; Prob. = 0 for MAMFA > 30; DF = 15	Prob. = 1 for MAMFA < 15; Prob. = 0 for MAMFA > 30; DF = 15	None
Mouth activation functions using oral inflator (after entering water) (MAWA), for INF	Prob. = 1 for MAWA < 15; Prob. = 0 for MAWA > 60; DF = 25	Prob. = 1 for MAWA < 15; Prob. = 0 for MAWA > 60; DF = 25	Prob. = 1 for MAWA < 15; Prob. = 0 for MAWA > 60; DF = 25	None
Mouth activation functions using oral inflator (after entering water) (MAWA), for HYB	Prob. = 1 for MAWA < 25; Prob. = 0 for MAWA > 60; DF = 25	Prob. = 1 for MAWA < 25; Prob. = 0 for MAWA > 60; DF = 25	Prob. = 1 for MAWA < 25; Prob. = 0 for MAWA > 75; DF = 25	None
Mouth activation functions using oral inflator (before entering water) (MAWB), for INF	Prob. = 1 for MAWB < 20; Prob. = 0 for MAWB > 60; DF = 30	Prob. = 1 for MAWB < 20; Prob. = 0 for MAWB > 60; DF = 30	Prob. = 1 for MAWB < 20; Prob. = 0 for MAWB > 60; DF = 30	None
Mouth activation functions using oral inflator (before entering water) (MAWB), for HYB	Prob. = 1 for MAWB < 30; Prob. = 0 for MAWB > 60; DF = 30	Prob. = 1 for MAWB < 30; Prob. = 0 for MAWB > 60; DF = 30	Prob. = 1 for MAWB < 30; Prob. = 0 for MAWB > 60; DF = 30	None

HYB = hybrid; INF = inflatable; DF = default value; Prob. = probability.

and their tests do not apply for a particular environment for the PFD. The default values cannot be used in lieu of testing, for certification, or for meeting standard requirements. The default values were selected through consensus by subject matter experts at special workshops held for this purpose.

## 5 Minimum Aggregate Performance

The minimum aggregate performance of a PFD is quantified in terms of two measures of effectiveness and success probability, where effectiveness has two parts of full and partial effectiveness, as follows:

- $P(\text{EFFL}|\text{AV}, \text{D}, \text{R})$  = probability that the PFD is properly effective given that it is available, donned, and reliable when PFD is used with full buoyancy (inflated). This value is determined as the weighted sum of performance measures of freeboard, face plane angle, heave period, turning ability, placement security, and detectability.

- $P(\text{EFFP}|\text{AV}, \text{D}, \text{R})$  = probability that the PFD is partially effective given that it is available, donned, and reliable when PFD is used with partial buoyancy (uninflated or partially inflated). This value is also determined as the weighted sum of performance measures of corresponding partial values of freeboard, face plane angle, heave period, turning ability, placement security, and detectability.
- $P(\text{S})$  = performance success probability of a PFD can be computed according to Eq. (1) as follows:  $P(\text{S}) = P(\text{AV})P(\text{D}|\text{AV})P(\text{R}|\text{AV}, \text{D})P(\text{EFF}|\text{AV}, \text{D}, \text{R})$ .

The minimum aggregate full effectiveness for  $P(\text{EFFL}|\text{AV}, \text{D}, \text{R})$  is 0.78, which is the probability that the PFD is effective when available, donned, and reliable. The minimum aggregate partial effectiveness for  $P(\text{EFFP}|\text{AV}, \text{D}, \text{R})$  is 0.78, which is the probability that the PFD is effective when available, donned, and reliable. The minimum values for  $P(\text{EFFL}|\text{AV}, \text{D}, \text{R})$  and  $P(\text{EFFP}|\text{AV}, \text{D}, \text{R})$  are the same; however, the underlying performance models for the two cases have different coefficients.

**Table 17(a) Recommended event probabilities relating to PFD users for all buoyancy methods for adults**

Event (symbol)	Open-water (OW) environment	Near-shore (NS) environment	Calm-water (CW) environment
PFD available (AV)	1	1	1
Person conscious after entering water (CA)	0.95	0.98	0.98
Person conscious   out of water (CP)	0.99	0.99	0.99
Environment does not impair donning in water (EDI)	0.5	0.7	0.7
Environment does not impair swimming (ENV)	0.6	0.775	0.8
Skill/knowledge to swim (KS)	0.7	0.85	0.85
Marine event (ME)	1	1	1
Person not fatigued   in water (NFI)	0.6	0.8	0.8
Person not fatigued   out of water (NFO)	0.9	0.9	0.9
Person not handicapped out of water (NH)	0.9	0.95	0.95
Person not handicapped in water (NHI)	0.87	0.9	0.9
Person not injured   in water (NII)	0.9	0.9	0.9
Person not intoxicated   in water (NINTI)	0.85	0.85	0.85
Person not intoxicated   out of water (NINTO)	0.85	0.85	0.85
Person not injured   out of water (NIO)	0.99	0.99	0.99

**Table 17(b) Example event probabilities relating to PFD users for all buoyancy methods for children**

Event (symbol)	Open-water (OW) environment	Near-shore (NS) environment	Calm-water (CW) environment
PFD available (AV)	1	1	1
Person conscious after entering water (CA)	0.95	0.98	0.98
Person conscious   out of water (CP)	0.99	0.99	0.99
Environment does not impair donning in water (EDI)	0.5	0.7	0.7
Environment does not impair swimming (ENV)	0.6	0.725	0.8
Skill/knowledge to swim (KS)	0.7	0.8	0.8
Marine event (ME)	1	1	1
Person not fatigued   in water (NFI)	0.6	0.8	0.8
Person not fatigued   out of water (NFO)	0.9	0.9	0.9
Person not handicapped out of water (NH)	0.9	0.95	0.95
Person not handicapped in water (NHI)	0.87	0.9	0.9
Person not injured   in water (NII)	0.9	0.9	0.9
Person not intoxicated   in water (NINTI)	1	1	1
Person not intoxicated   out of water (NINTO)	1	1	1
Person not injured   out of water (NIO)	0.99	0.99	0.99

**Table 17(c) Example event probabilities relating to PFD users for all buoyancy methods for infants**

Event (symbol)	Open-water (OW) environment	Near-shore (NS) environment	Calm-water (CW) environment
PFD available (AV)	1	1	1
Person conscious after entering water (CA)	0.95	0.98	0.98
Person conscious   out of water (CP)	0.99	0.99	0.99
Environment does not impair donning in water (EDI)	0.5	0.7	0.7
Environment does not impair swimming (ENV)	0.6	0.7	0.6
Skill/knowledge to swim (KS)	0	0	0
Marine event (ME)	1	1	1
Person not fatigued   in water (NFI)	0.6	0.8	0.8
Person not fatigued   out of water (NFO)	0.9	0.9	0.9
Person not handicapped out of water (NH)	0.9	0.95	0.95
Person not handicapped in water (NHI)	0.87	0.9	0.9
Person not injured   in water (NII)	0.9	0.9	0.9
Person not intoxicated   in water (NINTI)	1	1	1
Person not intoxicated   out of water (NINTO)	1	1	1
Person not injured   out of water (NIO)	0.99	0.99	0.99

The minimum success probability for PFDs is 0.5200, defined corresponding to a 0.9000 conditional success probability. The conditional success probability is based on the parameters of Tables 17(a-c) taking their maximum possible values of 1.

## 6 Web Tool and Examples

The PFDRA web tool was prepared to enable the assessment of a PFD design to save lives following marine events for the purpose

of verification of the models. It evaluated all the scenarios and results in probabilities of aggregate performance and lifesaving. It offered a formal structure and consistency for dealing with new concepts and special classes of PFD designs by establishing lifesaving probability equivalency to current standards and existing accepted designs. It also aided in identifying critical factors for the PFD performance necessary to establish equivalence. The tool was used to: (1) manage available PFDs, (2) enter data to analyze a new PFD, or (3) view sample PFDs in the database. Entering data on new PFDs was based on duplicating existing PFD records. The web tool

included many example cases. The tool was very helpful in developing the model; however it is not available to the public at present and not supported.

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## Appendix

### Heave Period Testing

The dynamic performance characteristics of a PFD are some of the attributes that affect the airway protection provided by the device, particularly when used in waves. In general, mouth immersions are more likely to occur when wearing a device with a longer natural heave period if all other characteristics are equal. Flotation attitude affects dynamic performance and the ability to effectively measure heave period. The natural heave period of the PFD system (the PFD and wearer combined) is to be evaluated by exciting the system vertically. Because the characteristics of the wearer influence the heave period of the PFD system, the heave period results are to be taken with a subject with specific size and flotation characteristics. Data shall be collected by videotaping the wearer in front of a grid (with a 25 mm (1 in.) or smaller horizontal line spacing.) To reduce the interference of waves, the test is to be conducted in a test tank that incorporates a gutter around the entire perimeter and that is filled to the top of the gutter (+7, -0 mm) or an equivalent arrangement. To represent someone that generally floats in a more vertical attitude, a male test subject who meets the following criteria shall be used:

- Height =  $1800 \pm 10$  mm ( $71 \pm 1$  in.)
- Mass = 70–90 kg (160–200 lb)
- In-water weight = 50–55 N (11–12 lb)
- Torso flotation angle in reference vest =  $35 \pm 7$  degrees
- Shoulder height = to be measured and recorded
- Waist height = to be measured and recorded
- Chest size = to be measured and recorded
- Waist girth = to be measured and recorded
- Neck circumference = to be measured and recorded
- Head circumference = to be measured and recorded

The test subject's height, dry mass, chest size, in-water weight, and flotation angle in the reference vest shall be measured to ensure that they comply with the above criteria. The additional anthropomorphic measurements above shall be recorded. Instruction and training shall be given to the subject, e.g., test procedures, relaxation or position-holding techniques, and breath holding.

The PFD is to be donned by the test subject in its intended manner and adjusted by the test engineer to a snug fit, and then the subject enters the water. Hybrid and inflatable PFDs shall be tested fully inflated. The test subject shall complete three bobs per the ride-up test procedure to ensure the PFD is properly secured and settled into the expected position on the wearer when being worn in waves and/or after swimming or assisting in abandonment. The test subject shall then to relax into a natural attitude of static balance. The face plane, torso, and body list angles shall be measured and recorded.

The subject shall be placed in front of a vertical grid with the zero grid line at the water level located at least 1000 mm (3 ft) from the gutter edge of the pool as shown in Fig. 9. The starting position of the subject shall be as close as possible to the grid. The subject

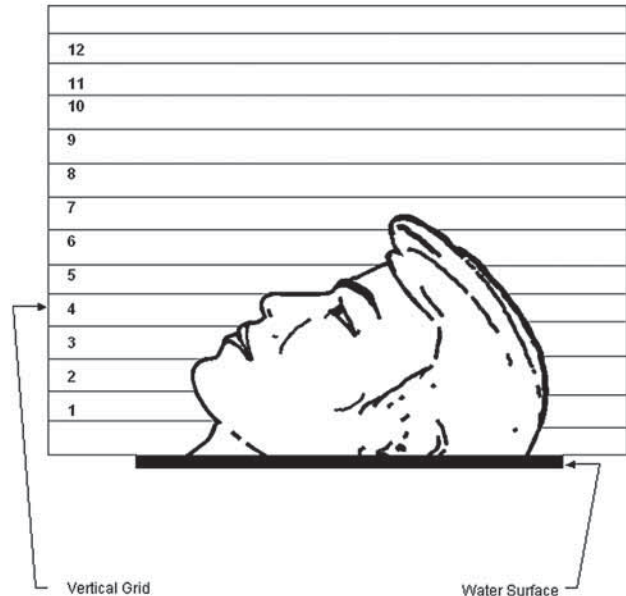


Fig. 9 Heave period test

shall not contact the grid during the test. The camera shall be positioned such that the center of the lens is at a height of 250 mm ( $\pm 25$  mm) ( $10 \pm 1$  in.) from the waterline, perpendicular to the grid, and at least 2.5 m from the subject to allow reading the displacement range of the subject's head after being excited with a vertical push.

The subject shall relax for at least 15 s and breathe normally while the face plane, torso, and body list angles are measured and recorded before any excitations. The subject shall hold a half breath (top of the tidal volume) while the test is conducted with the following posture: starting from a relaxed flotation attitude, stiffen the neck, bring the hands to the sides and feet together, and hold the stiffened arms and legs in that position. The subject shall be instructed that the stiffened positions are not to be excessively tense or rigid, but that the head or limbs should not be allowed to relax or move freely relative to the torso.

The method of initial excitation of the wearer/PFD system shall be in the vertical direction in a manner that minimizes splashing and pitching (body angle change) or movement in other than the vertical direction to the extent possible; the same torso angle needs to be maintained. The recommended method for excitation is to momentarily push downward and immediately release the subject. If there is excessive pitching induced, the procedure should be repeated by pushing down at another location closer to the center of buoyancy or if necessary by pushing at two locations to displace the subject with a minimum of change in body angle. The excitation should be sufficient to provide at least three complete heave oscillations after the wearer is released, or if the system damping does not permit three complete oscillations, multiple runs/tests shall be taken to provide at least three complete cycles.

This method requires a video processing software package that can import raw digital video and compress the video into frames. There are two standard frame rates, NTSC and PAL, which shoot at 30/1.001 (about 29.97) frames per second and 25 frames per second, respectively. Assigning a frame rate to the raw video allows one to establish time stamps to the hundredths of a second. The maximum height of movement of the head in the vertical direction shall be recorded after initial excitation. The corresponding frame time (FT1) shall also be recorded. The subject will then descend into the water. The lowest point may be recorded for half-cycle rates. The maximum height of movement of the head in the vertical direction shall be recorded for the next ascending cycle, along with its frame time (FT2). The heave period shall be calculated as follows:

heave period (seconds) =  $FT_2 - FT_1$ . Half cycles can be observed and doubled.

The repeatability of the system used shall be checked by running the test three times, and the results shall be within 15% in order for the system to qualify to such testing.

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