BOAT BOARDING LADDER PLACEMENT

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Presented in three volumes; "Boat Boarding Ladder Placement," which explores safety considerations including potential for human contact with a rotating propeller; "Boat Handhold Placement," which explores essential principles and methods of fall control; and "Bowrider Backrest Height Variables," which uses actual accelerometer data in various boats to develop a computer prediction model to explore backrest height as a factor in containing boat occupants during various maneuvers.

Results of the studies and experiments provide groundwork for possible voluntary industry standards development and possible development fo Federal regulations.

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Table of Contents

List of Tables

List of Figures

BOAT BOARDING LADDER PLACEMENT

INTRODUCTION

Background

During recent years, boat boarding ladder placement has been identified as one of several factors which could play a positive role in reducing propeller strike accidents. Miller, Grieser, and Clark (1996) documented the advantages and disadvantages of various possible boarding locations for typical mono-hull boats with important safety considerations including the potential for human contact with a rotating propeller. In one case, it has been suggested that prohibiting the location of boarding ladders or swim platforms near the propeller may help prevent propeller strikes (NBSAC, 1997).

The purpose of this present study, then, was to determine for boat manufacturers and designers the potential for various other reboarding positions around a boat perimeter relative to potential "propeller operation zones." This new term, propeller operation zone (or "POZ"), is being defined by the authors as the entire area representing any or all potential paths of the propeller once a boat's transmission is engaged in either forward or reverse for the various foreseeable purposes for which the boat is used.

The size and shape of POZ's are determined primarily by a vessel's turning behavior or maneuverability as well as the purpose and frequency of such maneuvering. There are four types of forces that affect a vessel's maneuverability (PNA, 1988):

1. Hydrodynamic forces on the hull and appendages resulting from the vessel's velocity; acceleration; outboard, sterndrive, or rudder deflection (ABYC P-17 and P-18 require outboard motor steering stops to allow 30 degrees minimum on either side of center); and propeller rotation,

2. Inertial reaction forces caused by vessel acceleration,

3. Environmental forces (e.g. from wind, currents, and waves), and

4. Other external forces (such as from towing a waterskier, another boat, or a PWC).

These forces in addition to the hull shape and vessel center of gravity determine a boat's maneuvering behavior and therefore the shape and size of the POZ for a given operational condition. The exact POZ for a given vessel design is most easily determined through water testing, but a ship controllability analysis could also be a feasible but relatively non-trivial approximation approach.

The authors recognize that the analyses presented herein may be applied to a variety of boat types including those which may better accommodate alternate boarding ladder locations such as houseboats and pontoon boats.

Prior Accident Data Collection

Until recently, if one attempted to determine the magnitude of the problem of propeller strike accidents, he or she would be confronted with three characteristics which have made the United States Coast Guard accident data inadequate to identify accurately propeller related injury or fatality incidents.

First, while the fatality statistics were believed to be fairly accurate, the Coast Guard's non-fatal injury and property damage numbers are believed to be considerably under-reported. In other words, as the accident severity level drops, so does the reporting rate. In past years, the Coast Guard injury data was estimated by the Coast Guard themselves to represent about 10 percent of the actual number of boat-related injuries (NCIPC, 1993). With recently revised accident data gathering methods, serious injuries are now believed to be better represented.

Second, the Boat Accident Reporting Form did not allow any distinction between nonfatal injuries/property damage caused by propeller strikes and nonfatal injuries/property damage caused by someone being struck by some other part of the boat. These two accident types were combined in the "struck by boat or propeller" category. The data gathering methods have recently been revised to make this distinction. Since this revision, recently published data indicates that 61 percent of these accidents involved "struck by boat" accidents and 39 percent involved "struck by propeller" accidents. It should be noted that the "struck by propeller" accidents include injuries with and without the propeller engaged and/or the engine running. Therefore, this category would include accidents such as a propeller blade laceration caused by someone stepping on and slipping from a sterndrive to board a boat with the engine off.

A third inadequacy in the Coast Guard accident data gathering methodology has also recently been improved. This problem involved the method in which accidents were classified. That is, accidents were classified into categories by the first event that occurred in the accident sequence rather than all events. For example, if an occupant falls out of a boat and is struck by a propeller, the accident was placed in the "falls overboard" category, not the "struck by boat or propeller" category. To help solve this last problem, the Coast Guard beginning with the 1992 boating statistics started reporting the totals of the first three events in fatal boating accident sequences. The proportion of fatalities attributed to "Struck by Boat or Propeller" for the next three years (1992-1994), was 3.5, 3.5, and 4.5 percent, respectively (USCG, 1992; USCG, 1993; USCG, 1994).

In response to an interest in additional data related to propeller strikes, the Coast Guard sponsored two accident studies in the early 1990s: a nationwide telephone survey conducted by the American Red Cross in 1991, and a study by the National

Center for Injury Prevention and Control (NCIPC), Centers for Disease Control and Prevention (CDC) completed in 1993.

American Red Cross Data
The Red Cross study consisted of a telephone survey sample of all households in the continental U.S. for the 1988-89 boating season. Survey subjects were asked to describe critical recreational boating accidents experienced within a year. If the survey subject had experienced more than one accident in the year, the causes, circumstances, and outcomes of the "most severe critical incidents" was selected for assessment in order to limit survey interview time.

Respondents reported incidents involving a person struck by a propeller in 1.1 percent of the incidents involving damage or injury. In comparison to propeller strikes, person was reportedly struck by a boat three times more frequently -- 3.3 percent of all accidents involving damage or injury. (Data such as this may help provide some insight into the proportion of each of these two types of events represented by the Coast Guard's combined category "struck by boat or propeller.")

NCIPC Data
The NCIPC study used National Electronic Injury Surveillance System (NEISS) data for propeller-related injuries collected from September 1, 1991, to August 31, 1992. NEISS is the primary data collecting tool for the Consumer Product Safety Commission (CPSC). The system receives injury reports from approximately 100 representative United States hospitals for consumer product-related injuries in which victims were given emergency room treatment.

NCIPC's analysis of NEISS data indicated that propeller injuries represent 2 to 2.5 percent of the total boat-related injuries. However, NCIPC determined from injury event narratives that only 13 percent of the injuries occurred with the engine on. Well over half (58 percent) of these injuries occurred with the engine off, and the engine status could not be determined for 29 percent of the injuries. It should be noted that the NEISS data also includes propeller injuries such as lacerations that occur while the boats out of the water (such as on trailers for storage or maintenance).

NCIPC also analyzed the NEISS propeller injury data relative to the "activity or operation" at the time of the propeller injury. The activity or operation most affected by boarding ladder placement was "Entering/Leaving Vessel" (3.0 percent of boat propeller related injuries). However, "Maneuvering" (3.7 percent of boat propeller related injuries), and "swimming" (16.7 percent of boat propeller related injuries) were propeller injury related activities in which boarding ladder placement may have been a factor. However, it is likely that at least some of the injured swimmers were not in any way associated with the parties in the striking boats. These potential boarding ladder-related activities therefore could hypothetically have been a factor in a maximum of 23.4 percent of the boat propeller related injuries. Any of the this data must be considered suspect and its reliability questioned since the largest category of activities were classified as "Other" (49.3 percent) and 8.1 percent of the activities were classified as "Unknown."

Task Stratification

In consideration of the "activities or operations" named in the above data sources which are likely affected by boarding ladder location, the authors have stratified examples of tasks or activities in which a person might be engaged just before being struck by a propeller:

- boat occupant entering water to swim, water ski, etc.
- reboarding boat
- in-water maneuvering, snorkeling, or swimming
- diving/jumping into water from various position inside or on the boat (e.g., stern, gunwale, bridge, or bow)
- sliding down a water slide (commonly aft-mounted on houseboats)

METHODOLOGIES

To accomplish the objectives of this study, six different types of analyses were considered to objectively identify and evaluate the potential hazards within propeller operation zones which might serve as potential reboarding positions around a boat's perimeter:

1. Propeller Operation Zone ("POZ")Analysis
2. Probability Distribution Analysis
3. Markov Analysis
4. Kinematic Analysis
5. Design Alternative Evaluation/Human Error Analysis
6. Attribute Analysis

1. Propeller Operation Zone ("POZ") Analysis

Procedure
This analysis consisted of identifying and graphically depicting POZ's around a typical boat at rest in the water. POZ's are bounded primarily by the four propeller paths during the smallest radius turn in each of four turning configurations as listed in the following table.

Table 1: Turning Configurations for Zone Determination

Turn No.	Longitudinal Direction	Transverse Direction
1	Forward	Port
2	Forward	Starboard
3	Aft	Port
4	Aft	Starboard

These above four turn maneuvers are illustrated in **Figure 1**.

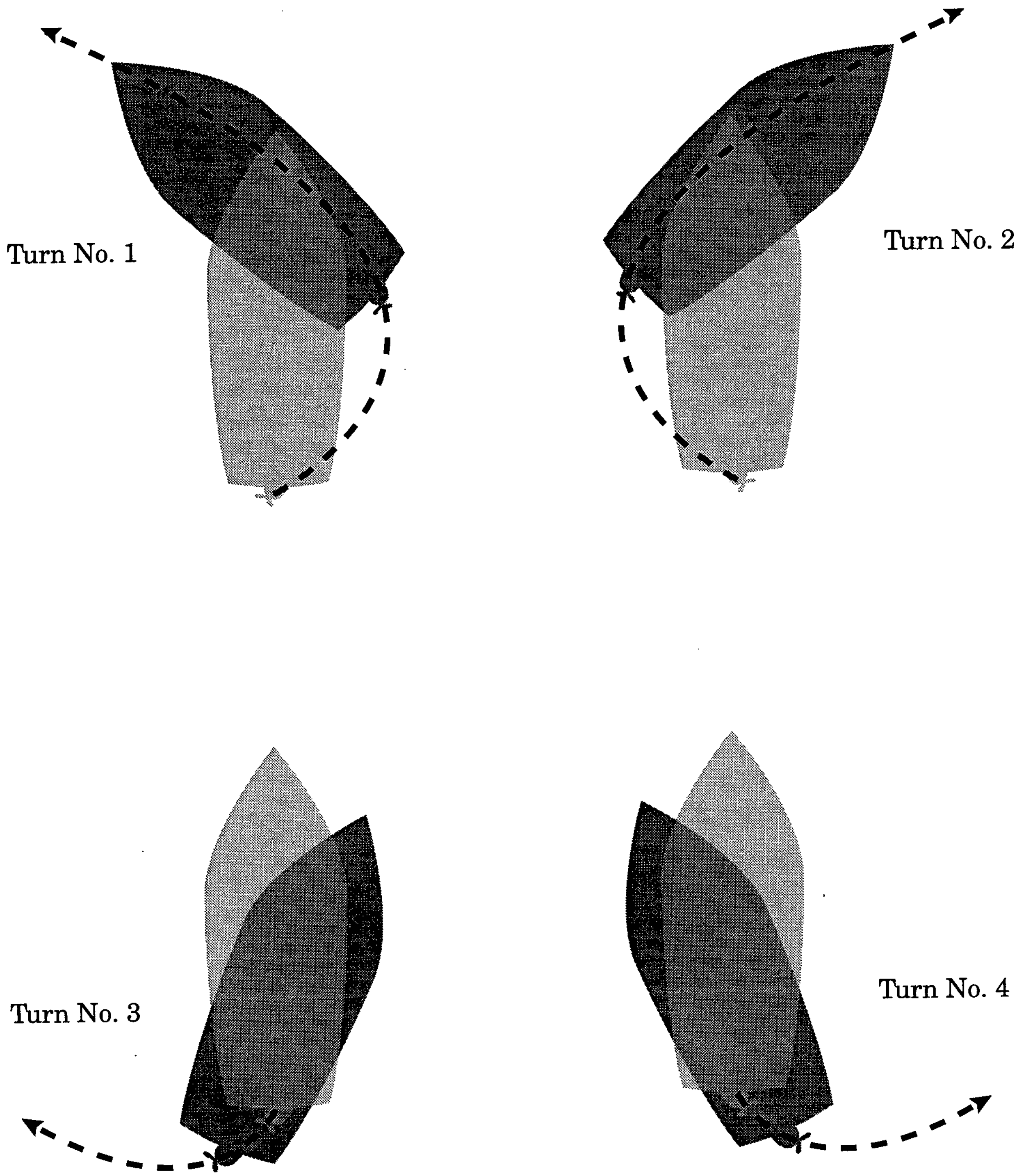

Figure 1: Propeller Operation Zone (POZ) Boundary Generation for All Possible Propeller Movement Locations (Forward Port Turn, Forward Starboard Turn, Rearward Port Turn, Rearward Starboard Turn)

Results

The POZ diagram (**Figure 2**) illustrates the potential forward and rearward propeller paths for a hypothetical vessel design. Most conventional boat designs likely have a POZ shape somewhat similar to this. Again, **Figure 1** shows the four boat turn maneuvers used to generate the POZ boundaries. These zone boundaries are represented as dotted lines in the figures. The two small propeller operation areas next to each side of the bow (labeled "3" and "4" in **Figure 2**) fall outside the areas of the boundary maneuvers. Nevertheless, these two areas are included as part of the POZ because the propeller can travel through these areas during forward turns at less than full rudder.

In creating the POZ diagram in **Figure 2**, the following assumptions were made:

- the environmental and external forces are zero (i.e. no wind, currents, waves, or objects being towed)
- there is no forward or reverse direction change
- other helm controls (e.g., steering)are also held constant once the propeller is engaged

The POZ's are only intended for illustrative purposes in this report. They do not necessarily represent the POZ's of any particular boat, and there are, of course, variations. For example, single screw inboards generally back in only one direction depending on the propeller rotation. Right-handed screw inboards normally back to starboard, and left-handed screw inboards to port. Thus, the aft portion of a POZ for a single screw inboard would be half the size of that pictured in **Figure 2**. That is, depending on the direction of propeller rotation, either area 7 or area 8 (in **Figure 2**) would be outside the operation zone .

Note that the POZ includes all possible propeller and boat movement locations, but does not indicate the probability that a propeller/boat will be at any particular position within a zone. Therefore, the next step is to recognize that within each of the zones, the higher the likelihood of a prop to occupy that zone when a swimmer or other person is in the water, the higher the likelihood for an injury. Thus, it is necessary in our evaluation to consider probabilistic models of propeller convergence on ladder locations.

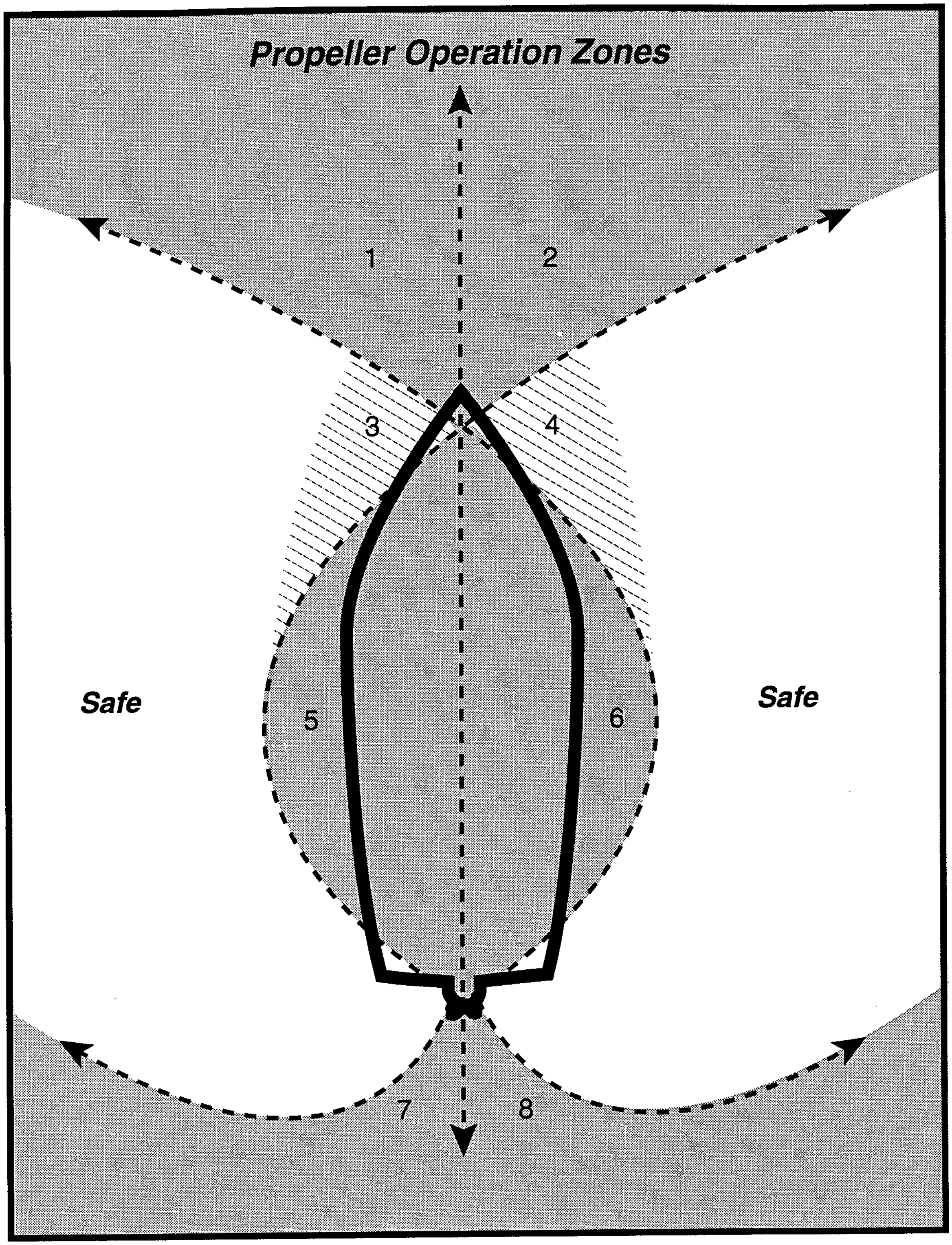

Figure 2: POZ Example

2. Probability Distribution Analysis

Procedure / Results

A propeller path probability distribution could be calculated for various boats and if the data was available. Until such time that this data is collected, the authors propose the hypothetical distribution illustrated in **Figure 3**.

The contour or "equiprobability" lines pictured represent potential propeller path locations of equal likelihood during a selected time duration for all expected maneuvers. Again, the same assumptions (from the POZ analysis) were made:

- the environmental and external forces are zero (i.e. no wind, currents, waves, or objects being towed)
- there is no forward or reverse direction (gear case) change
- other helm controls are also held constant once the propeller is engaged

These equiprobability line locations for a vessel are dependent on several variables affecting maneuverability and speed of maneuvering including:

- power
- weight/distribution
- hull shape
- propulsion type
- propeller rotation
- propeller characteristics such as pitch and diameter
- outboard, sterndrive, or rudder deflection (ABYC P-17 and P-18 require outboard motor steering stops to allow 30 degrees minimum on either side of center)
- vessel velocity
- vessel acceleration
- turning radius

The POZ analysis developed earlier in this report was used as a guide for the equiprobability line boundaries. Equiprobability lines are essentially equivalent to depth lines in nautical charts which show connected points of equal water depth.

A propeller location probability distribution is useful for determining how likely that a boarding ladder location is within a potential propeller path. For example, one can see from **Figure 3** that a boarding ladder placed near the vessel's centerline at the stern is within the most likely propeller location area (probability =0.475), while a ladder placed outboard to either side is completely outside the propeller location area (probability < 0.05). Ladders mounted at the bow or on the gunwales are in the 0.3 to 0.4 probability areas. (Note: all probability values are hypothetical only.)

In evaluation of the aft boarding ladder locations locating outside of the POZ, example swimmer locations are represented by dashed circles five feet in diameter (**Figure 4**). This relatively large diameter was chosen in recognition of the dynamic nature of the swimming/water treading motions in the potentially wavy environment as one approaches a ladder. The port side dashed circle pictured in **Figure 4** illustrates that an aft-mounted ladder may be located outside the POZ,

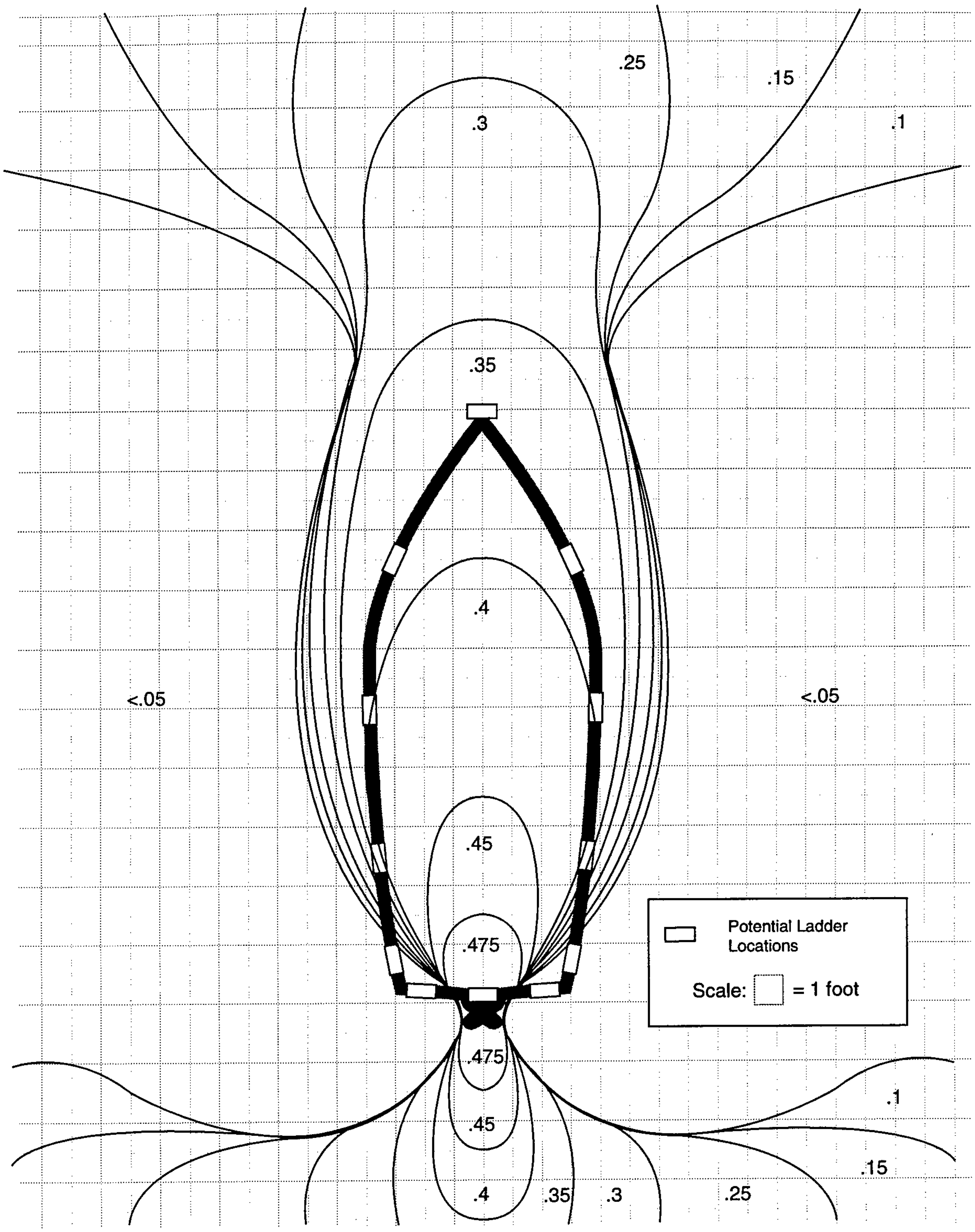

Figure 3: Propeller Zone Probability Distribution

yet close enough to it that some propeller contact is possible. This is indicated by the dashed line that intersects the propeller location area. On the other hand, shifting the boarding ladder location approximately one foot outboard also shifts the associated circular swimmer area out of this high probability area (as illustrated by the starboard side dashed circle in **Figure 4**). Potential side-mounted ladders represented by this aft outboard location include those mounted on the side of a swim platform (probably feasible on many boats with swim platforms including houseboats) or on the aft gunwale (probably less feasible as boats are designed today).

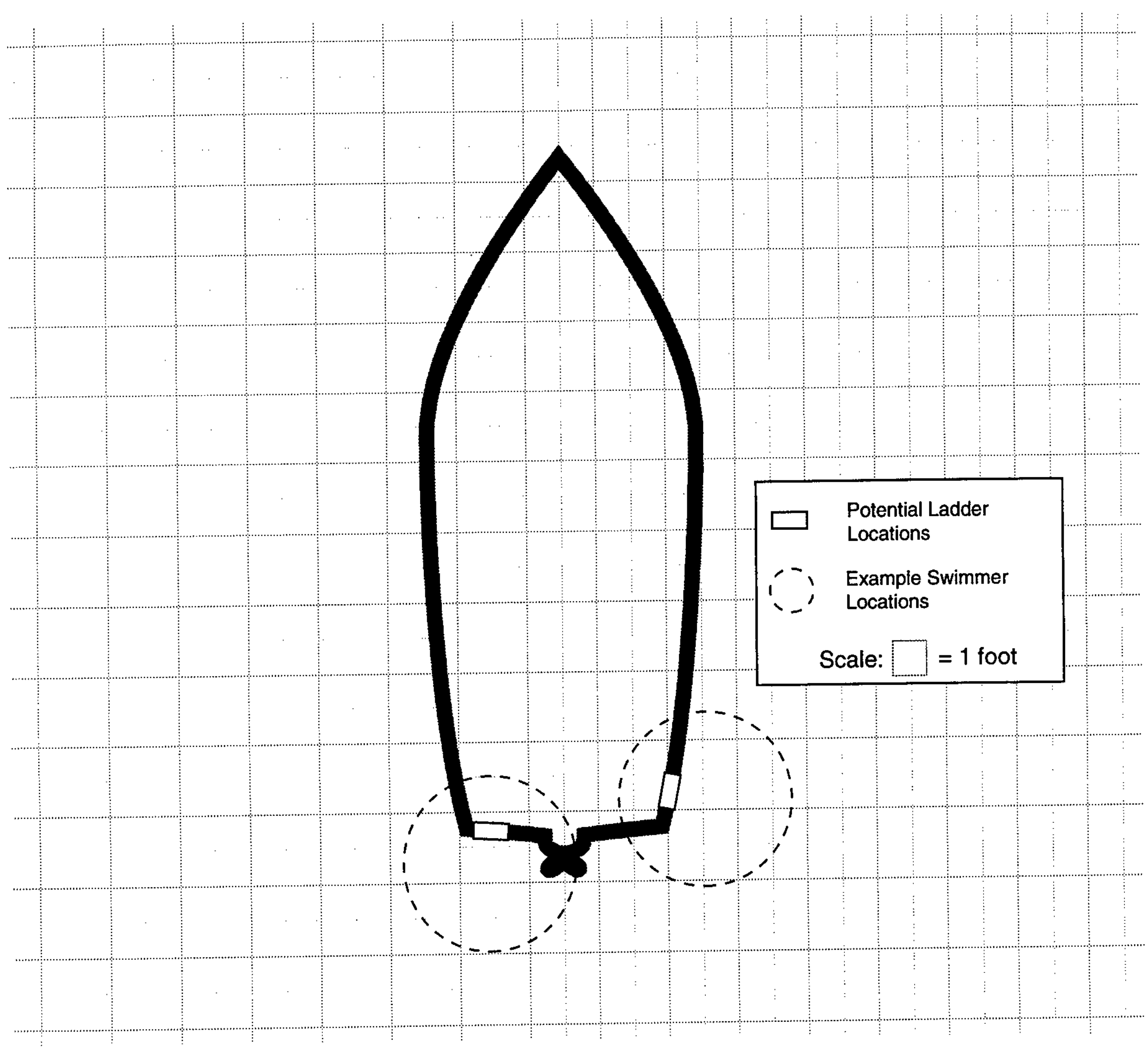

Figure 4: Swimmer Areas at Boarding Ladders Outside POZ

3. Markov Analysis

The use of Markov chains is a common statistical data analysis method that can be used to analyze the probabilities associated with a sequence of events. Human factors engineers often conduct such an analysis to determine with respect to time the probability of a future process or event state given the present (or past) state. For example, an investigator using eye movement data to study visual scanning patterns in a cockpit may be interested in which instrument the operator looks at after looking at the tachometer. Markov chains have also been used to determine the optimal strategy in various baseball game scenarios. For example, it is possible to predict the statistically optimal batting order, or the expected scoring of moving from one base runners and outs combination to another (such as if a manager is considering whether a sacrifice bunt to move a certain number of runners over one base is worth the additional likely out).

In this study, the application of a Markov type analysis might be appropriate for the prediction of the future propeller position (with respect to a potential boarding ladder location) given a present propeller and boarding ladder position. The link between the present and future boarding ladder locations is called a transition probability matrix.

Transition Probability Matrix (General)

Future Propeller Location One Time Interval Later (X_{n+1})

$$
\text{Present Propeller Position } (X_n) \quad
\begin{array}{c|cccccc|}
 & 1 & 2 & 3 & \text{---} & k \\
\hline
1 & p_{11} & p_{12} & p_{13} & \text{---} & p_{1k} \\
2 & p_{21} & p_{22} & p_{23} & \text{---} & p_{2k} \\
3 & p_{31} & p_{32} & p_{33} & \text{---} & p_{3k} \\
- & - & - & - & & - \\
- & - & - & - & & - \\
- & - & - & - & & - \\
k & p_{k1} & p_{k2} & p_{k3} & \text{---} & p_{kk}
\end{array}
$$

Where:
p_{ij}= the probability of moving to j from i

The one-step transition probability of moving from state i, at time n, to j, at time $n+1$ in one time interval is defined by the following equation.

One-Step Transition Probability

$$P[X_{n+1}=j \mid X_n=i]=p_{ij}(n)$$

Where:
X = random variable (e.g., ladder location)
i = first state
j = second state
n = time

Thus, to predict potential future propeller locations, one needs only the location probability distribution so that a transition probability matrix can be generated. The problem is that such data has not been collected by these or other researchers.

In lieu of collecting such data, an attempt was made to generate a hypothetical probability distribution as a first step toward illustrating the Markov analysis technique.

To provide a simplified numerical example of the application of Markov chains to the boating arena, the POZ may be divided into seventeen sections with the first section representing the current location as shown in **Figure 5**. One could probably also subdivide the POZ into many more sections for greater precision.

For purposes of simplicity, we will consider only the first row of the transition probability matrix as shown below (which represents only the transitions from position "1"):

$$\begin{array}{cc|ccccccccccccccccc|}
 & & & & & & & & & & & X_{n+1}\ \text{(Future)} & & & & & & & \\
 & & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 & 16 & 17 \\
\begin{matrix} X_n \\ \text{(Present)} \end{matrix} & 1 & p_{11} & p_{12} & p_{13} & p_{14} & p_{15} & p_{16} & p_{17} & p_{18} & p_{19} & p_{110} & p_{111} & p_{112} & p_{113} & p_{114} & p_{115} & p_{116} & p_{117}
\end{array}$$

Let's then assume the following (estimated) probability values in the transition probability matrix:

$$\begin{array}{cc|ccccccccccccccccc|}
 & & & & & & & & & & X_{n+1} & & & & & & & & \\
 & & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 & 16 & 17 \\
X_n & 1 & .01 & .1 & .1 & .1 & .1 & .08 & .075 & .08 & .075 & .06 & .02 & .06 & .02 & .04 & .04 & .02 & .02
\end{array}$$

Note that the sum total of these seventeen probabilities is 1.0, meaning areas "1" through "17" represent all the possible propeller locations after one time duration later.

In summary of the above example, a propeller at the "1" position as shown in **Figure 5** would move after a specified time duration to:

Position...	**With Probability...**
1 (no movement)	.01
2, 3, 4, or 5	.1
6 or 8	.08
7 or 9	.075
10 or 12	.06
14 or 15	.04
11, 13, 16, or 17	.02

A caveat to this present analysis is that it only predicts the probabilities of future propeller locations and not the paths traveled in transition to these locations. Relative to propeller strikes potential, the path location is, of course, just as important as the propeller's ultimate location during a specified time period. Nevertheless, when attempting to arrive at objective measures for making rational decisions on a matter, multiple approaches can give some assurance that a single criteria or approach has not been overweighted in a final determination or recommendation.

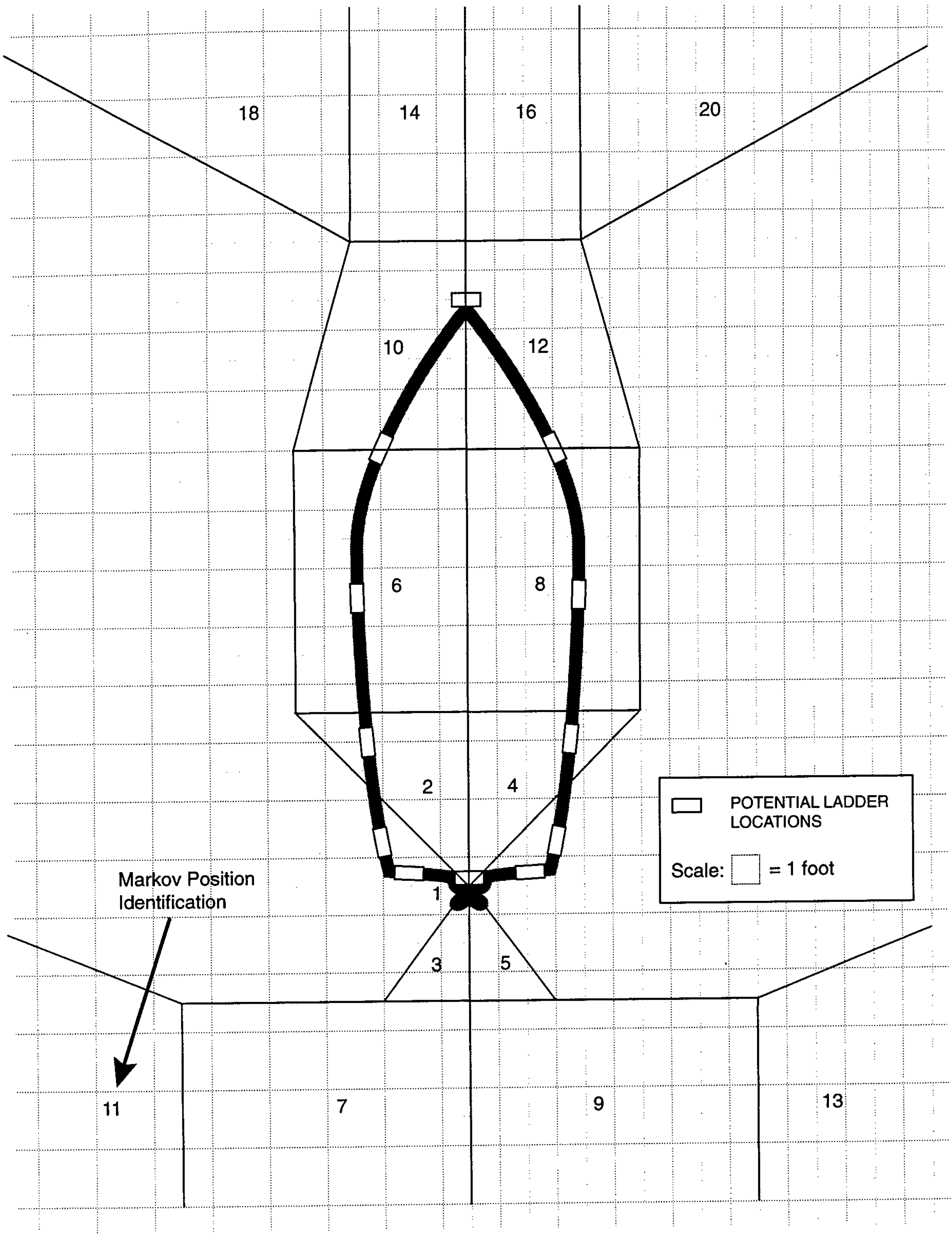

Figure 5: POZ Markov Subdivision

4. Kinematic Analysis

As yet another approach, we developed a kinematics analysis. This evolved out of the recognition that an important consideration for boarding ladder placement is the distance from the propeller. The further a boarding ladder is located from the propeller, the longer the time required for the propeller to pass near the location of that boarding ladder. **Figure 6** depicts potential boarding ladder locations for a 20 foot boat (for a scale of one square of the grid = one foot). If one assumes that a typical boat runs three miles per hour on average when placed in gear (but no further throttle applied), then, **Table 2** below lists the time for a propeller to travel to each of the potential ladder locations. The last column adds one second to the raw calculated times to allow for boat acceleration from zero. The propeller travel times can easily be normalized up (or down) depending on the size of the boat. For example, for a sixty foot houseboat, the raw times are simply multiplied by three (60ft/20ft = factor of three greater); consequently, the time needed for the propeller to reach the bow boarding ladder position might be about fifteen seconds on the houseboat but only five seconds for a twenty foot runabout. Such additional time may be adequate for a vigilant swimmer to avoid being struck by the propeller.

How much time might be required for a swimmer to avoid a propeller strike? An estimate of the time from the onset of the stimulus (the propeller moving towards the swimmer) to the point at which he or she begins to execute the response would range from one to five seconds depending on the circumstances. This would leave a minimum of ten (15 - 5 = 10) seconds for swimmer execution of the chosen avoidance task for the sixty foot houseboat case, but leave possibly no time (5 - 5 = 0) for the twenty foot runabout.

Where does this estimation one to five seconds come from? The total time needed for a human complex reaction to an external stimulus can be broken down into four components (the one to five second estimation used above is the sum of the first three components below):

1. Encoding of Stimulus Information -- approximately 0.1 seconds
2. Central Processing (stimulus identification from comparison of encoded stimulus information with similar stimuli in memory) -- approximately 0.4 seconds
3. Response Selection -- up to 4 seconds
4. Response Execution -- varies depending on complexity of required response

The total time required for these four reaction time components can vary greatly depending on several factors including: the sensory channel through which the stimulus is initiated, the stimulus characteristics, whether the stimulus is anticipated, and the body members used in response execution.

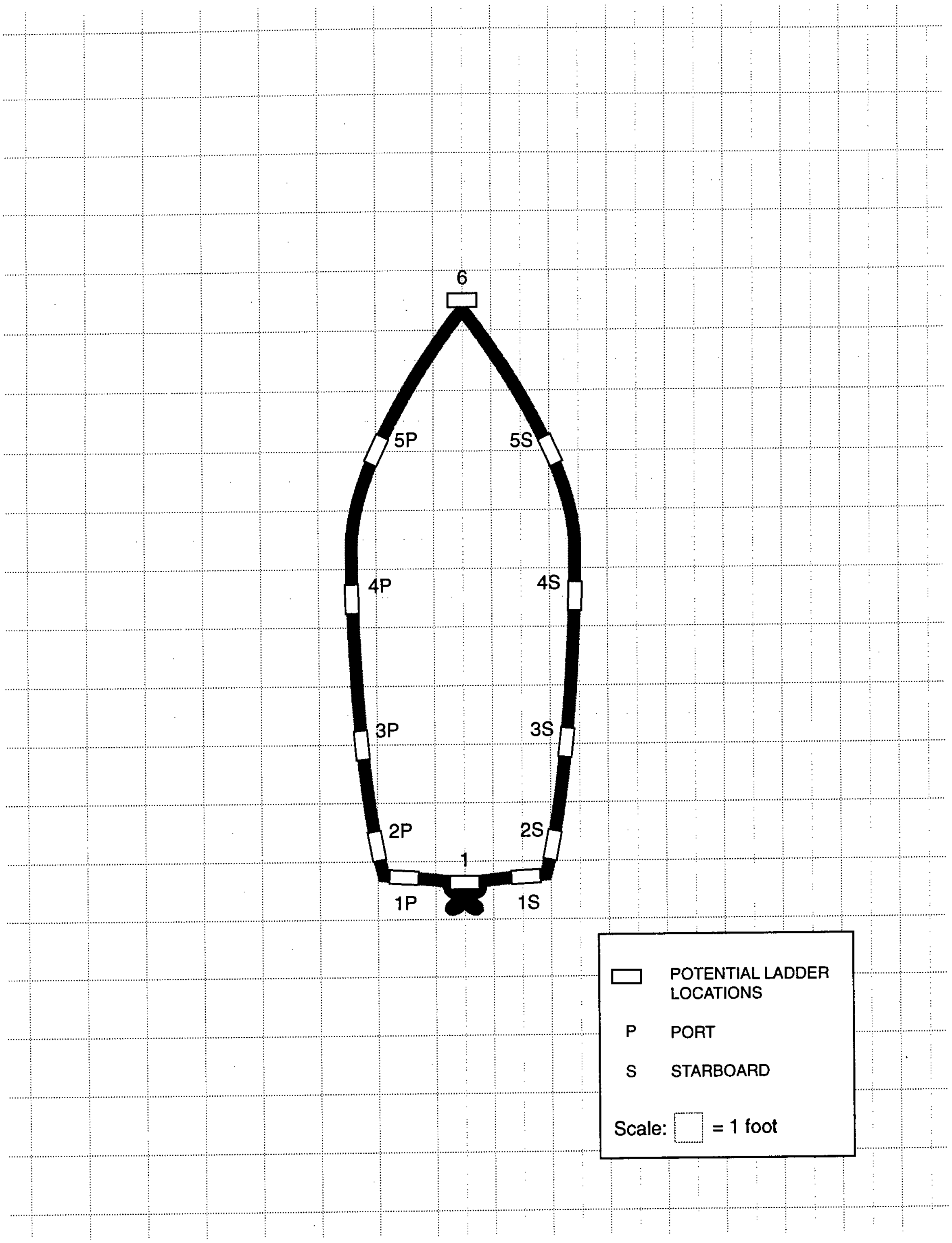

Figure 6: Kinematic Analysis Diagram

Table 2: Kinematic Analysis Results

Potential Ladder Location (from Fig. 4)	Approx. Distance (ft)	Raw Propeller Travel Time to Ladder (sec)	Propeller Travel Time to Ladder (sec)*
1	0	0	1
1P, 1S	1	∞	∞
2P, 2S	2.5	∞	∞
3P, 3S	5	1.1	2.1
4P, 4S	10	2.3	3.3
5P, 5S	15	3.4	4.4
6	20	4.6	5.6
Other Locations on Longer Boats	40	9.1	10.1
	60	13.6	14.6
	80	18.2	19.2
	100	22.7	23.7

* Includes 1 second added to raw propeller travel time to allow for boat acceleration time
∞ = infinite travel time (propeller cannot reach ladder location)

5. Design Alternative Evaluation/Human Error Analysis

Background

When someone is struck by a boat propeller the striking propeller may be from the boat to which the swimmer is resident, or from other adjacent boats. A necessary question to answer is: "Why are swimmers injured by boat propellers?" A few of the possible answers to this question include: accidental activation of helm controls, steering wheel turned in wrong direction when throttle activated, operator lack of knowledge of swimmer in area, boat occupant ejection, etc.

In the case of boat propeller strikes, there are essentially three categories of contributing accident causes:

1. Helm Errors: (e.g., lack of experience; impairment by alcohol intoxication, drug use, or fatigue; inattentiveness, unsafe judgment; and carelessness/recklessness)

2. Swimmer Errors: (e.g., lack of experience; impairment by alcohol intoxication, drug use, or fatigue; inattentiveness, unsafe judgment; and carelessness/recklessness)

3. Adverse Environmental Conditions: (e.g., wind, currents, low visibility conditions such as fog or darkness, and waves).

Ladder location is one of the boat design features that has been singled out in recent years for analysis with the thought that there may be a correlation between ladder location and frequency of propeller strikes. If we presume that there is a correlation, then, as a result of our analysis we might propose the following criteria: Well placed ladders should be:

1. outside the most likely propeller paths,
2. within direct or peripheral view of helm, and
3. away from propeller area.

Procedure / Results

In order to compare the various available boarding ladder locations in view of the above three contributing accident causes and the POZ, a conceptual design engineering analysis adapted from Pugh (1991) is useful. Pugh's analysis method consists of a technique to evaluate possible design concepts or solutions to a particular problem.

Using the necessary criteria that he or she chooses, the designer compares potential design solutions to the existing design (or datum). For each criterion, the designer simply scores each alternative as better than (+), worse than (-), or the same as (S) as the datum. The total number of +'s, -'s, and S's are then summed which reveals strengths and weaknesses of the various concepts in comparison to the datum.

To illustrate how this type of analysis works, **Table 3** was developed as an example. The table columns represent the various potential boarding ladder locations, and the rows represent many of the potential contributing accident causes. A stern-mounted starboard ladder location was arbitrarily chosen as the datum to which all the other ladder locations were compared. In "low visibility" conditions (found in **Table 3** under the third sub-heading "Environmental Conditions" in the first column), it would be expected that a swimmer adjacent to a boarding ladder located near the helm (assuming helm on starboard side) in the helmsperson's direct or peripheral view would be more easily seen than at the stern. Therefore, a "+" is marked in the columns representing ladder locations where visibility of the boarding ladder area is better than at the datum (stern-mounted starboard) ladder location, and a "-" is marked in columns where visibility is worse than at the datum. Consequently, the starboard bow and side columns contain a "+", and the columns representing locations opposite the helm contain a "-". If the visibility is the same, or if it is not determinable how the location compares to the datum, the appropriate location is marked with a "0". (The bow amidships column contains a "0".) One then continues in this same fashion to complete the analysis.

These choices represent the authors' engineering judgment, and the rankings used in similar future analyses can be modified, if necessary, to reflect new data.

Table 3: Accident Contribution Analysis

Primary Contributors to Accident	Stern Port	Stern Amid	Stern Stbd	Bow Port	Bow Amid	Bow Stbd	Side Port	Side Stbd
Helm Errors:								
Lack of Experience	-	-	D	-	0	+	-	+
Impairment	-	-		-	0	+	-	+
Inattentiveness	-	-		-	0	+	-	+
Unsafe judgment	-	-		-	0	+	-	+
Carelessness/recklessness	-	-		-	0	+	-	+
			A					
Swimmer Errors:								
Lack of Experience	0	-		0	0	0	+	+
Impairment	0	-		0	0	0	+	+
Inattentiveness	0	-		0	0	0	+	+
Unsafe judgment	0	-	T	0	0	0	+	+
Carelessness/recklessness	0	-		0	0	0	+	+
Environmental Conditions:								
Wind	0	0		-	-	-	-	-
Low visibility	-	-	U	-	0	+	-	+
Waves	0	0		-	-	-	0	0
Currents	0	0		-	-	-	0	0
Totals:								
Sum "+"	0	0	M	0	0	6	5	11
Sum "-"	6	11		9	3	3	7	1
Sum "0"	8	3		5	11	5	2	2

Datum = Ladder location to which other locations are compared (starboard stern)
+ = Safer (less likely to result in propeller strikes than datum)
- = Less safe (more likely to result in propeller strikes than datum)
0 = Same likelihood, or difference is indeterminable

6. Attribute Analysis

A boarding ladder location attribute analysis was performed as part of a previous study by these authors and is included in this report as Appendix D.

CONCLUSIONS/RECOMMENDATIONS

The only locations on boats outside the propeller operation zones (POZ's) in most cases are the outboard aft extremes of the vessel. This means that a person swimming at either of the rear corners of a boat is probably outside of potential propeller paths but not necessarily out of range of direct contact. Based on this analysis, it would also seem logical to locate boarding ladders at the stern as far outboard as possible or on either the port or starboard sides as far aft as possible to prevent direct contact (such as on the side of a swim platform, for example).

While some have argued that the bow area is a safer location for a boarding ladder than the stern (because the bow is furthest from the propeller), the bow area is in the forward path of the propeller, which is the propeller's most likely path. Also, the bow can obstruct the helmsperson's vision of swimmers who are near it. Finally, swimmer detection of propulsion engine(s) starting or running (which can provide an auditory warning signal that propeller engagement possible) is more difficult at the bow than at the stern. In consideration of these factors, it is feasible that moving the boarding ladders to the bow could possibly <u>increase</u> the number of propeller strikes rather than decrease them.
On the other hand, the bow area is furthest from the propeller and therefore would allow a vigilant swimmer some additional time to move away from the propeller path or to take some other avoidance action. On a relatively long boat such as a houseboat, this distance may become more important since this additional time could equal as much as <u>10 to 20 seconds</u> or more. However, data would need to be collected relative to the dependence of swimmers' probability of avoiding propeller strikes on their initial distance from the propeller.

We would conclude that for most boats, including houseboats and pontoons, the outboard aft areas are the locations most often outside of the propeller operation zone. Therefore, stern ladders mounted as far outboard as possible, and side-mounted ladders (if feasible) located as far aft as possible will most likely be outside the propeller operation zone. Where visibility and communication with swimmers is possible from the helm, starboard (helm) side mounted boarding ladders would be preferable to port side mounted ladders (Miller, Grieser, and Clark, 1996).

Because the bow area is easily within the POZ and because swimmers can be visually obstructed by the bow, this area would not appear to be safer than the aft mounting locations recommended above even though it is furthest from the propeller. There currently is not enough data available to determine to a scientific level of certainty whether a change in boarding ladder location would have a significant effect on the number of propeller strikes to swimmers resident to the host boat.

SUGGESTIONS FOR FUTURE STUDY

For the purpose of future design or standards development, determination of POZ's for particular boat models empirically is fairly straightforward. An analytical zone calculation algorithm may also be possible though non-trivial, but its accuracy would need to be verified with empirical data.

The probability data needed to perform a Markov-type boat movement analysis would require a fairly extensive data collection effort and may not be the best use of available resources at this time. Studies that could yield more immediate useful results include:

1. A human factors experiment to test the effect of boarding ladder placement on operator likelihood to shift a boat in gear toward a swimmer

2. A study to determine the effect of warnings, swimmer education, driver education, and/or boat operating procedures on preventing swimmers in the stern area from direct propeller contact.

Appendix A

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Appendix B

Phase II Ladder Placement/Stability Section

LADDER PLACEMENT

Introduction/Background

For *most* boats, permanently installed side ladders are not practical because they are so prone to damage during docking maneuvers and during turns. Historically, the universal location for permanently mounted boarding ladders on planing monohulls is at the stern. However, there is not a clear choice as to which side the stern ladders should be mounted (port or starboard). Over the last several years this question has generated much debate and controversy, yet there has been no clear "winner." The purpose of this section is to provide boat designers considerations for making a sound decision based on the different variables they encounter in the design process.

The stern not only provides a reasonably safe location for the ladder, but also the most hydrostatically stable location for reboarding. One may argue that at the stern, the propeller presents a hazard during reboarding, but a person climbing into the boat at the stern may be in no greater danger than someone at the side of boat. If the boat was inadvertently put into gear, a person on the side of the boat would be also within the zone of the propeller. In order to remain furthest away from the propeller while in the stern area, the outboard edges of the transom are the preferred location for reboarding ladders. The question then is, "Which side of the transom is most appropriate?" This study attempts to address that question.

Current Industry Practice

In order to determine where boat manufacturers locate their stern mounted boarding ladders (port or starboard), thirty-three representative builders' design practices for the 1995 model year were studied.
Of the thirty-three manufacturers:

- Twenty-two (67%) locate their boarding ladders for their various models on the port (non-helm) side of the stern
- Nine (27%) locate their boarding ladders for their various models on the starboard (helm) side
- One manufacturer (3%) installs boarding ladders on the starboard side for all of its models except for two
- One manufacturer (3%) provided boarding ladders on both port and starboard sides

Additional specifics about the boats surveyed (such as length and beam) were not analyzed to see if the ladder location may be correlated with some size parameter.

Discussion

When determining boarding ladder placement, there are at least six key considerations that the boat designer should carefully evaluate with respect to any particular boat. These key ladder placement considerations include:

1) stability
2) visibility from helm/helm location
3) vulnerability of ladders to damage during docking and turning
4) propulsion type/distance from propeller (if boat has one)
5) freeboard
6) boat dynamics
7) general convenience

The following table summarizes the strengths and weaknesses of various boarding ladder placements based on the above design considerations.

Table II-6: Port vs. Starboard Boarding Ladder Location

	Pros	Cons
Port Stern	Potential for greatest stability because opposite helmsperson.	Nearest position to propeller (for non-water jet propelled vessels).
	Helmsman does not have to turn around as far to see the skier/swimmer board boat.	If helmsperson approaches swimmer on port side, he or she may not be able to see swimmer nearly as well because of the obstruction the gunwale presents.
	Stern provides overall location of least motion.	If helmsman keeps swimmer on starboard side on an approach, then swimmer must cross propeller area.
Starboard Stern (Helm side)	Superior overall stability.	Nearest position to propeller (for non-water jet propelled vessels).
	As vessel is brought up to skier/swimmer, helmsperson can keep person in view and more easily guide ladder to person.	Could cause a stability problem on relatively light, narrow boats with person boarding on same side as helmsperson.
	Because there may be more weight starboard, the ladder may be easier to use since it will be lower in the water.	
	Stern provides overall location of least motion.	
Bow	Furthest boarding location distance from propeller.	Swimmer may be occluded from helmsperson's view by bow.
	Convenient for ingress into a beached boat.	Swimmer in forward path of propeller.
		A vulnerable location to boat pitching motion which could make boarding more difficult.

Port Gunwale	Further immediate distance from propeller than at stern locations.	On typical mono-hulls, stability may be inferior.
		Swimmer may be occluded from helmsperson's view by gunwale
		Ladders may be vulnerable to damage during docking and turning.
		Major design changes may be necessary in ladders and in hull design and structure.
		Potentially high gunwale to climb over.
		A vulnerable location to boat rolling motion which could make boarding more difficult.
Starboard Gunwale (Helm Side)	Probably best visibility of swimmer.	On typical mono-hulls, stability may be inferior.
	Communication with swimmer probably easiest.	Swimmer may be occluded from helmsperson's view by gunwale
		Ladders may be vulnerable to damage during docking and turning.
		Major design changes may be necessary in ladders and in hull design and structure.
		Potentially high gunwale to climb over.
		A vulnerable location to boat rolling motion which could make boarding more difficult.

Recommendation

Boat stability should be the first consideration, especially for relatively small, light, narrow boats. For larger, heavier boats, visibility "displaces" stability as the primary consideration.

A stability analysis criteria needs to be developed to help analyze reasonable options for ladder locations. The smaller the boat, the more critical is such an analysis, which could limit reasonably safe ladder locations. In the case of the smaller boats, the analysis would probably point toward a port stern ladder mounting location. An example of a criterion that could be used in this analysis might be: "With the weight of a swimmer, helper, and helmsperson all on one side (probably starboard) of the boat in the stern, if the freeboard becomes less than 'X' inches, then port side stern mounting is probably more justified."

Since the analysis that we have performed here and the suggestions we have provided have not been done before, we cannot be critical of boat manufacturers' current design practices. Port or starboard mounting would both now be considered the state-of-the-art.

Conclusion

Taking all things into consideration, there would seem to be more arguments in favor of a stern mounted ladder on the starboard (helm) side, provided the specific boat involved would not suffer stability problems when such ladder were used. We believe that it would be possible to provide quantified criteria to specify with what specific designs these stability considerations would make helm side mounted stern ladder inadvisable. Any standard developed to address this issue would have to recognize the performance differences which would result with different hull designs, relative to a helm side stern ladder. In general, most of the smaller, lighter, narrower boats would have to be excused from having the helm side mounting. With a large volume of the boats sold being of this size, it may well be that the current practice of having about two-thirds of the boarding ladders on the port stern would not change, but at least there would be an engineering rationale for the decision to have the ladder placed in this location.

BOAT HANDHOLD PLACEMENT

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Table of Contents

List of Tables

List of Figures

Boat Handhold Placement

INTRODUCTION

Boats are dynamic objects whose six degrees of motion are at times unpredictable to their occupants. In addition, boats are also often wet and have reduced slip resistance. Consequently, when people desire to move in, on, or around a boat, or simply maintain a given position within a boat, precautions are necessary to maintain static and dynamic stability and to avoid falls and other undesirable body movements. Maintaining one's stability means preventing falls overboard, drowning (by far, the leading cause of death from boating accidents), and even boat and underwater gear strikes.

There are certain essential principles and methods of fall control which can be applied to the boating environment. (See "Designs of Boat Handholds and Boarding Ladders: Principles and Examples," Miller, Grieser, and Clark 1996). In changing elevation or moving, the usual points of support in body movement are, of course, the hands and feet. Each limb in firm contact with the boat represents one point of stability. If one limb slips, recovery is facilitated by the remaining limbs in firm contact which must provide the leverage points for regaining stability. For example, when walking on a level surface, each foot in firm contact during the walk is a support point. When standing still on both feet, two points of contact exist. When balanced on one foot at any time, one point of contact exists. Walking, thus, involves somewhere between one and two points of contact. When a person slips while walking, one may temporarily lose one point of contact. Depending on the phase of the walk movement where a slip is initiated, it may or may not be recoverable by quickly re-establishing another point of contact with the other foot or with a hand, using some type of dedicated or other handhold.

Thus, the likelihood of recovery from any slip often depends on how many points of contact are available to assist in the recovery. Climbing ladders is a particular task where the 3-point contact principle can be applied. For example, on a ladder or a ladder like system, a person usually maintains three points of contact , while a free fourth limb is moving toward a progressive location. Therefore, if the person experiences a fall initiation at one of the three points of contact, there is a much higher probability for recovery because of the other two contact points that still exist to assist in the recovery. In a boat, as in some other modes of transportation (i.e., bus, plane, ship, train, or subway) the probability that a person will need the full three points of contact increases as motion variability increases, slip resistance decreases drastically, or where the predictability of either slip resistance or motion decreases.

The purpose of this study was to provide boat manufacturers/designers an illustrated methodology for determining potential placement points for handholds (or other structural features which can serve as handholds) such that three point (or at the very least, two point support) can be maintained.

Such methodology will hopefully lead to increased occupant stability and, therefore, decrease the frequency of losses of balance which lead to falls. Boat manufacturers will ultimately be able to use such methodologies to also communicate to users in their product information how an occupant should utilize the available boat features to maintain stability. Depending on the success of the methodology developed, it may be possible for consensual (ABYC) or governmental (USCG) standards to be developed in relation to certain types of boat categories, and in relation to occupants engaged in certain frequent and foreseeable tasks.

Any development of a standard requires consideration of whether such standard will be of a "performance" type or "design/specification" type. In the present instance it is likely that a performance standard would be appropriate. Such performance criteria language is always controversial. Nevertheless, we wish to propose the following as the first version of such performance criteria:

Fall Prevention Safety Criteria in Boats

The attributes of a boat of a certain size or style can be evaluated relative to Fall Prevention Safety by determining the extent to which that boat has physical design characteristics which facilitate an occupant's ability to:

A. maintain balance/stability while seated or standing in an intended location;

B. maintain balance/stability while transitioning in or about the boat along intended pathways;

C. reduce the potential for fall initiation caused by a
    (1) foot slip,
    (2) hand slip, or
    (3) loss of balance; and to

D. provide a physical design which facilitates recovery from a fall initiation.

The present study will have as one of its objectives, the testing of these criteria under actual circumstances to begin assessing their feasibility as part of a future standard.

METHODOLOGY

To accomplish this feasibility study, task analyses were performed to identify for a given boat which of several types of occupant movements are likely to happen based on the starting and ending points of the various potential movement maneuvers. Several series of photographs were taken during typical boat occupant tasks to demonstrate some of the ways that it is possible to maintain a stable posture while using available handholds in combination with other boat interior components. Usually, 3-point contact was available for critical parts of the movements.

Handhold Use Tasks

Table 1 lists movement or stabilization tasks typical of boat occupants moving in and around a boat. The list is obviously not exhaustive.

Table 1: Example Handhold Use Tasks (adapted from Miller, Grieser, and Clark, 1996)

Task	Task Description
A	Maneuvering from bow seating area to/from cockpit
B	Maneuvering about a console
C	Transitioning from swim platform to sun deck to cockpit (and vice versa)
D	Maneuvering about cockpit fore to aft (and vice versa)
E	Maneuvering about cockpit port to starboard (and vice versa)
F	Emergence from water and transitioning onto swim platform (and vice versa)
G	Transition from main seating area to bow platform (and vice versa)
H	Maneuvering about bow seating area
I	Stabilization at bow seat
J	Stabilization at center position of bench seat
K	Ingress/egress
L	Stabilization at other seats
M	Maneuvering about a swim platform

These tasks can generally be broken into the following five components:

1. Start position/location (of static body)
2. Preparation for transition (identify and contacting initial stabilization points)
3. Transition (from one stable position to another stable position)
4. Preparation for end position (identify and contact final stabilization points)
5. End position/location (of static body)

Test Boat

The boat chosen for demonstrative purposes in this study was a late model bowrider stern drive. It was selected as having characteristics typical of contemporary recreational runabouts (**Table 2**).

Table 2: Test Boat Characteristics

Model Year	Length (ft)	Type	Hull	Material	Propulsion
1997	17	Bowrider	Semi -vee	FRP	Stern drive

The authors recognize that other widely used boat types exist. However, the methodology developed here can easily be applied to most other common boat types. The constraints of this project did not allow us to broadly apply this methodology to other typical types of boats or other seating configurations. For this boat we conducted nine tasks to demonstrate the feasibility of utilizing the criteria above. We further analyzed one of them in detailed tabular form, the results of which are described in the following.

RESULTS

Appendix B consists of the photographs taken as part of this study. These photographs illustrate nine of eleven occupant tasks listed previously in **Table 1**. In each of the tasks, the subject maintains three point contact throughout the five task components: 1) start position/location, 2) preparation for transition, 3) transition, 4) preparation for end position, and 5) end position/location.

Figure 1 consists of a sample photographic sequence illustrating the three point contact method for Task K: "Ingress/Egress." **Table 3** is the result of a sample three point contact analysis of the **Figure 1** sequence. This analysis tracks each sequential limb movement, and the associated number of points of contact with each change in posture during the task. Similar analyses can be performed for each of the handhold use tasks represented in the **Appendix B** photographs. **Appendix C** is an index to the **Appendix B** photographs. In this index, each photograph is labeled by film roll, photograph number, task type, and task location.

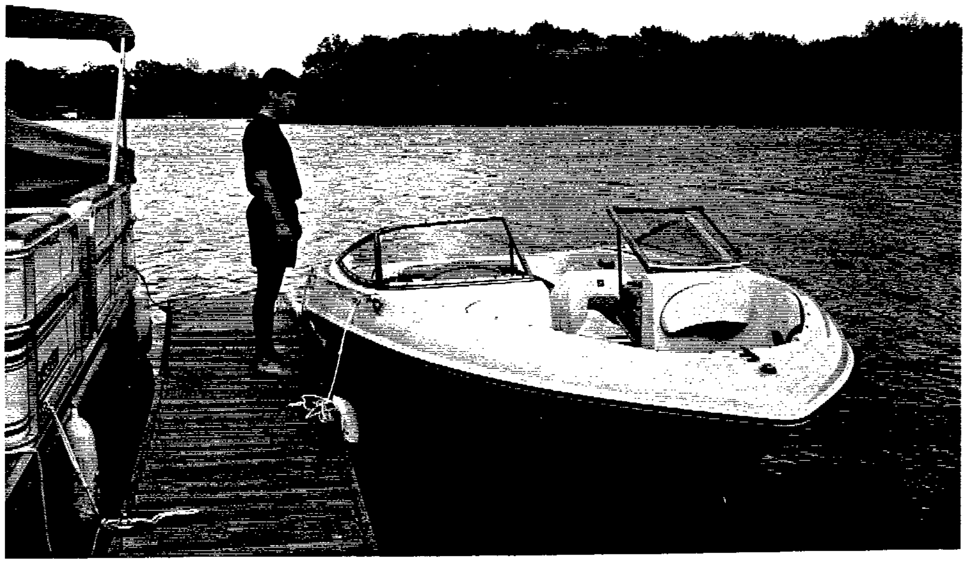

Figure 1a: Sample Handhold Use Sequence, Task K: Ingress/Egress, Step 1

Figure 1b: Sample Handhold Use Sequence, Task K: Ingress/Egress, Step 2

Figure 1c: Sample Handhold Use Sequence, Task K: Ingress/Egress, Step 3

Figure 1d: Sample Handhold Use Sequence, Task K: Ingress/Egress, Step 4

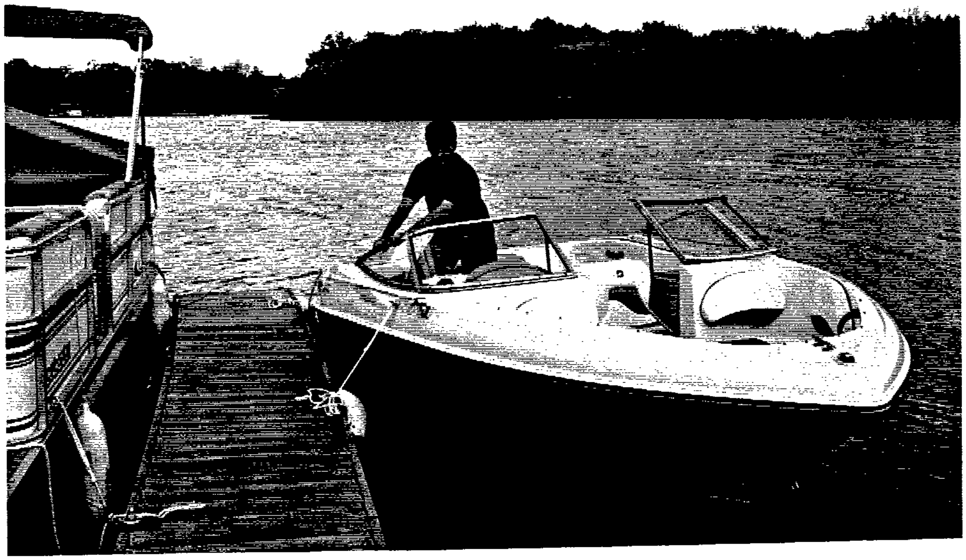

Figure 1e: Sample Handhold Use Sequence, Task K: Ingress/Egress, Step 5

Figure 1f: Sample Handhold Use Sequence, Task K: Ingress/Egress, Step 6

Table 3: Sequential Three Point Contact Analysis Example, Task K: Ingress/Egress

Task Component	Postural Progression	Left Hand	Right Hand	Left Foot	Right Foot	Total Points of Contact	Photo Number in Sequence
1. Start Position/ Location	**Standing on Dock about to Board**	No Contact	No Contact	Dock	Dock	2	1
2. Preparation for Transition	**Left and Right Hands Grab Windshield**	Windshield	Windshield	Dock	Dock	4	2
3. Transition	**Left Foot Moves toward Seat**	Windshield	Windshield	In Motion	Dock	3	-
3. Transition	**Left Foot Contacts Seat**	Windshield	Windshield	Seat	Dock	4	3
3. Transition	**Right Foot Transferred into Boat**	Windshield	Windshield	Seat	In Motion	3	-
3. Transition	**Right Foot Contacts Seat**	Windshield	Windshield	Seat	Seat	4	4
3. Transition	**Left Foot Lowered to Floor**	Windshield	Windshield	In Motion	Seat	3	-
3. Transition	**Left Foot Contacts Floor**	Windshield	Windshield	Floor	Seat	4	5
3. Transition	**Right Foot Lowered to Floor**	Windshield	Windshield	Floor	In Motion	3	-
5. End Position/ Location	**Right Foot Contacts Floor/Left hand releases windshield**	No Contact	Windshield	Floor	Floor	3	6

DISCUSSION/RECOMMENDATIONS

The photographs represent only a few of the virtually unlimited methods for providing adequate support to boat occupants. The examples presented are not necessarily the best or most innovative, but are represented as solid examples of how the physical characteristics of a boat can satisfy our suggested Fall Prevention Safety Criteria for Boats, repeated below:

Fall Prevention Safety Criteria in Boats

The attributes of a boat of a certain size or style can be evaluated relative to Fall Prevention Safety by determining the extent to which that boat has physical design characteristics which facilitate an occupant's ability to:

A. maintain balance/stability while seated or standing in an intended location;

B. maintain balance/stability while transitioning in or about the boat along intended pathways;

C. reduce the potential for fall initiation caused by a
   (1) foot slip,
   (2) hand slip, or
   (3) loss of balance; and to

D. provide a physical design which facilitates recovery from a fall initiation.

Unfortunately, the implementation of the suggested criteria will not prevent all falls in even the most well-designed boats. One obvious reason for this is that occupants can neither be required to perform only those tasks in a boat which can be done safely, nor be forced to utilize three point support even when available. However, those prudent occupants will be much better protected from falls by following manufacturer, Coast Guard, and industry association recommendations to maintain three point support, if their vessel provides for it.

This study has provided an illustrative methodology for boat manufacturers to determine if additional handholds are needed given the natural or inherent structural members already present in a given boat model. Boat manufacturers also now have a guideline for communicating through their product information how an occupant should utilize the available boat features to maintain stability. For example, the Appendix B photographs, or other similar photographs, can be easily converted to graphics for boat owner's manuals or other product information.

We would conclude that, with additional feasibility testing across a broader variety of boats and tasks, some version of the suggested Fall Prevention Safety Criteria in Boats could be incorporated into a future ABYC or Coast Guard performance standard.

SUGGESTIONS FOR FURTHER STUDY

Extension Study #1: Recommended Walkways

It is already known that the above named Fall Prevention Safety Criteria will not be attainable in all boat sizes and styles. In such cases, some limitation on use of certain areas may be necessary for safety reasons. For example, there may be reasons to identify a recommended walkway/movement area for relatively small, light boats below a specified stability. The bottom of a small aluminum fishing boat might be painted a different color to mark areas where an occupant can safely step. To determine a boat's safe walkway area, criteria could need to be established for the amount of allowable change in draft, heel, trim, and/or freeboard for a representative weight placed at the designated walkway edge. Designated walkway/movement areas may also be similarly marked on platform-style boats such as bass boats.

Extension Study #2: Boat Owner's Manual Chapter

Using the Fall Prevention Safety Criteria along with the **Appendix B** photographs, a boat owner's manual chapter could be developed. The chapter might be titled "Fall Prevention", or "Avoiding Falls In or Around Your Boat", or "Safe Movement In and About Your Boat." It would be designed so that it could be easily integrated into boat manufacturers' current or future owner's manuals. Professional quality line drawings would be generated from the Appendix B photographs to illustrate the concept of three point contact in boats. Accompanying explanatory language would be written at a level such that it could be comprehended by nearly all boat owners. While defense against litigation claims would not be a motivation for including such materials, such instructions to occupants might reduce loss-of-balance/fall-related incidents and, subsequently, reduce the frequency or severity of litigation outcomes.

Extension Study #3: Handhold Ergonomics

It is desirable to encourage handhold use by ergonomically designing them not only so that they can be quickly and easily accessed when needed, but also so that they are both comfortable and natural to grasp for relatively long durations. Design elements affecting handhold ergonomics include placement, orientation, size, texture, shape, etc. This proposed study would therefore attempt to answer questions such as: "At boat locations where occupant postures may be fairly predictable (e.g., seat locations), how can boat handholds be ergonomically designed for increased usage and accessibility by a relatively large percentage of the user population?"

Appendix A

References

Miller, J.M., Grieser, B.C., Clark, D.R. (1996). "Designs of Boat Handholds and Boarding Ladders: Principles and Examples," *Occupant Protection Phase II*, DOTCG Grant No. 130202, NTIS PB96 195839XSP, Final Report to U.S. Coast Guard, April.

Appendix B

Handhold Use Photographs

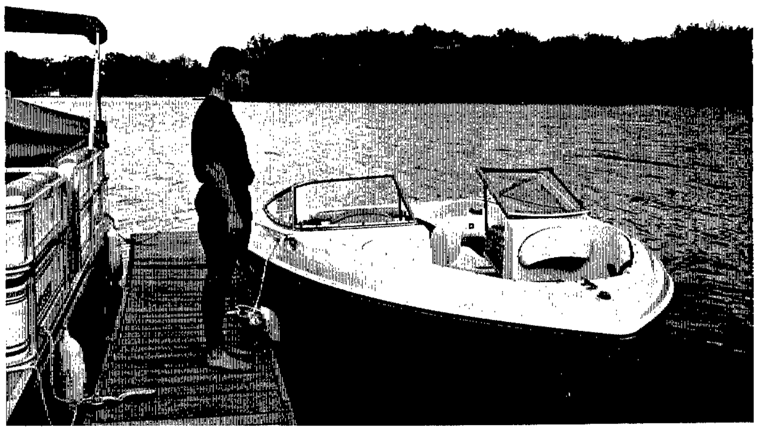

Photo A-0 Task K. Ingress/Egress Bow Step 1

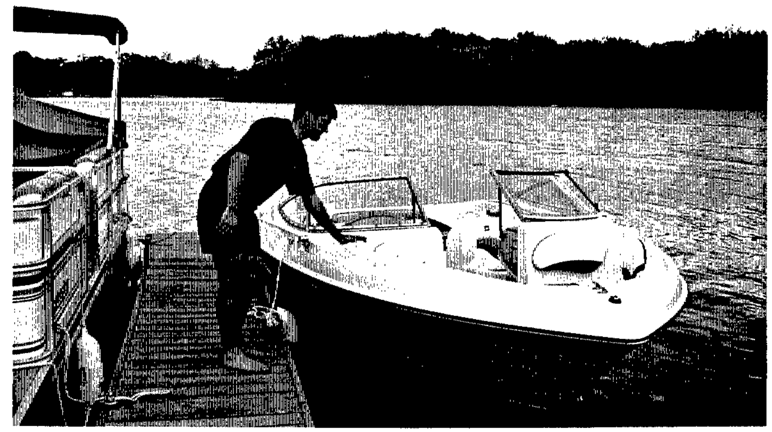

Photo A-1 Task K. Ingress/Egress Bow Step 2

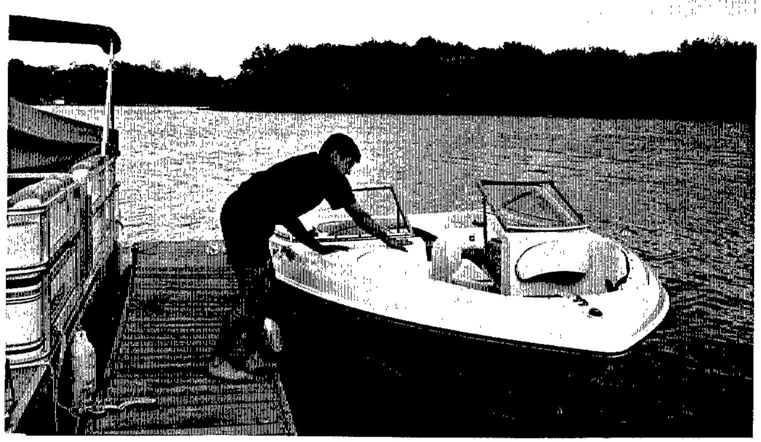

Photo A-2 Task K. Ingress/Egress Bow Step 3

Photo A-3 Task K. Ingress/Egress Bow Step 4

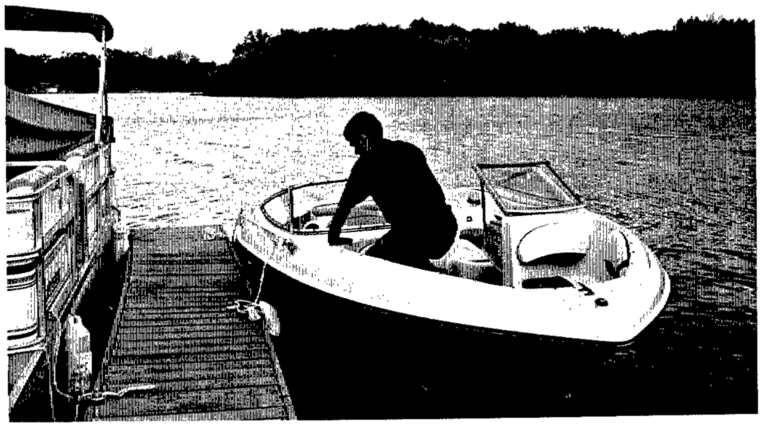

Photo A-4 Task K. Ingress/Egress Bow Step 5

Photo A-5 Task K. Ingress/Egress Bow Step 6

Photo A-6 Task K. Ingress/Egress Bow Step 7

Photo A-7 Task K. Ingress/Egress Bow Step 8

Photo A-8 Task K. Ingress/Egress Bow Step 1 Trial 2

Photo A-9 Task K. Ingress/Egress Bow Step 2 Trial 2

Photo A-10 Task K. Ingress/Egress Bow Step 3 Trial 2

Photo A-11 Task K. Ingress/Egress Bow Step 4 Trial 2

Photo A-12 Task K. Ingress/Egress Bow Step 5 Trial 2

Photo A-13 Task K. Ingress/Egress Bow Step 6 Trial 2

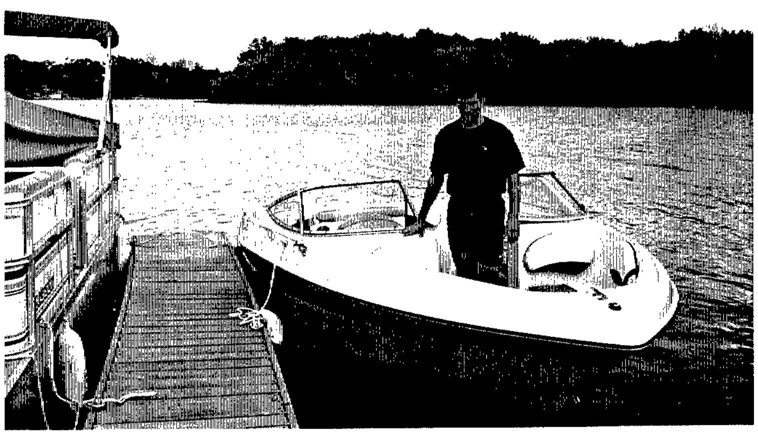

Photo A-14 Task K. Ingress/Egress Bow Step 7 Trial 2

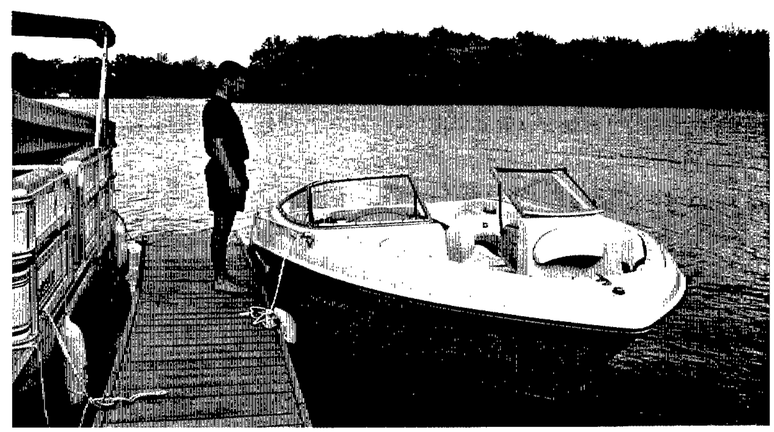

Photo A-15 Task K. Ingress/Egress Amidships Step 1

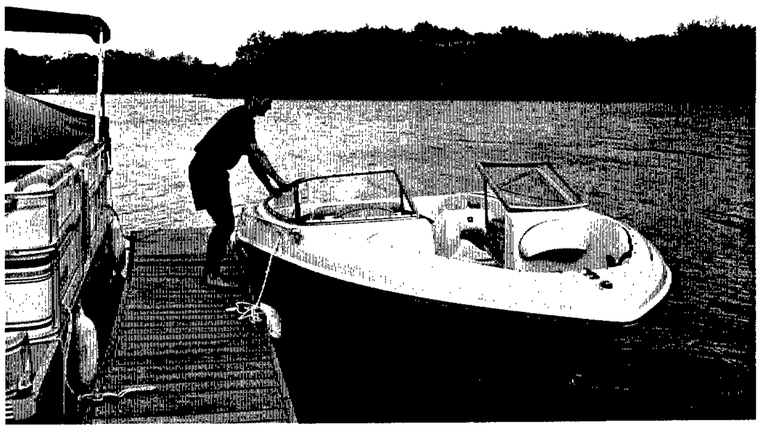

Photo A-16 Task K. Ingress/Egress Amidships Step 2

Photo A-17 Task K. Ingress/Egress Amidships Step 3

Photo A-18 Task K. Ingress/Egress Amidships Step 4

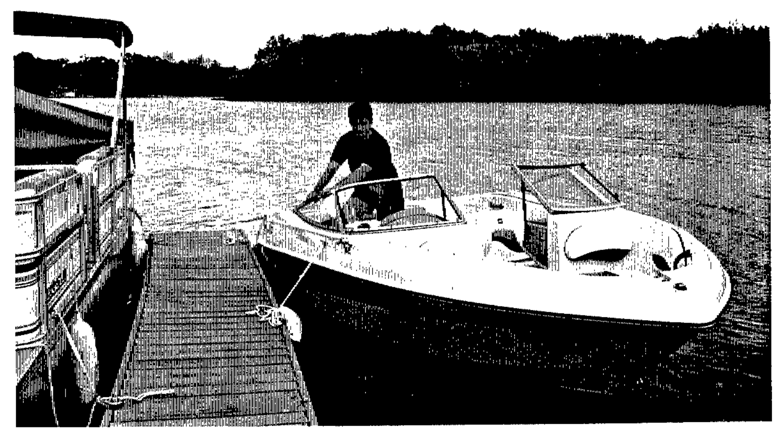

Photo A-19 Task K. Ingress/Egress Amidships Step 5

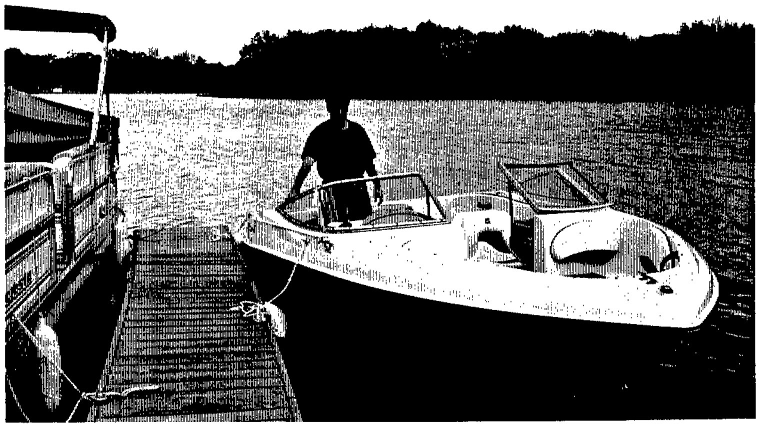

Photo A-20 Task K. Ingress/Egress Amidships Step 6

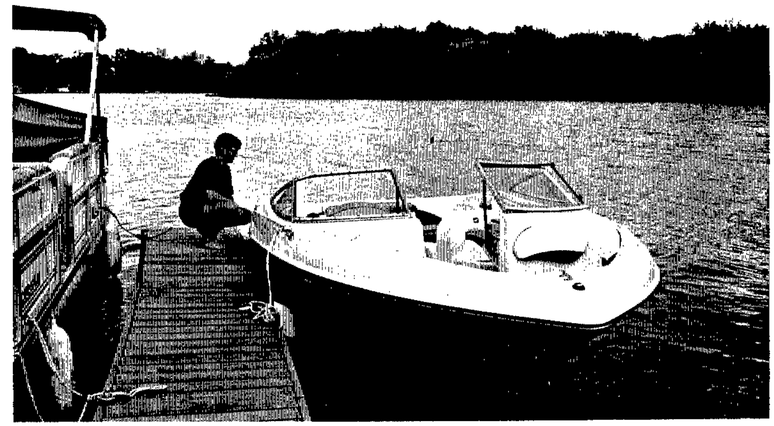

Photo A-21 Task K. Ingress/Egress Stern Step 1

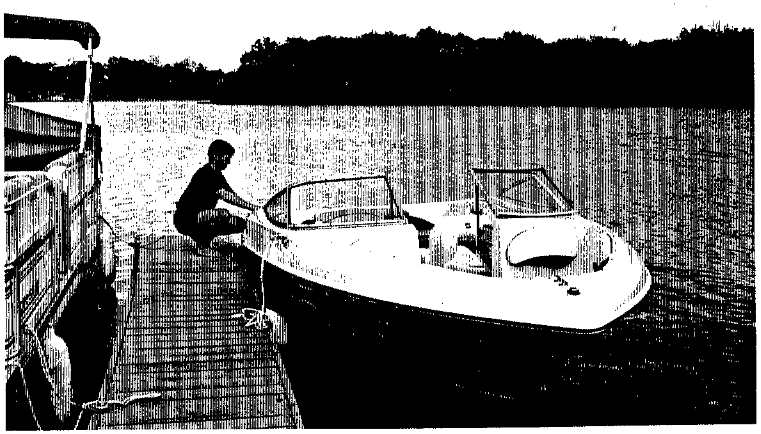

Photo A-22 Task K. Ingress/Egress Stern Step 2

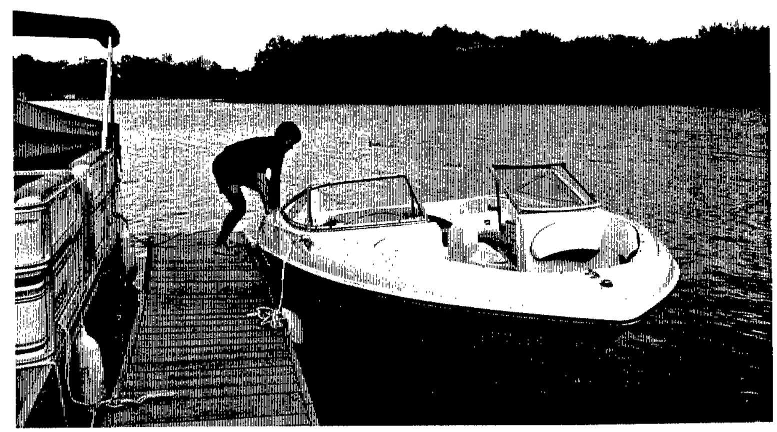

Photo A-23 Task K. Ingress/Egress Stern Step 3

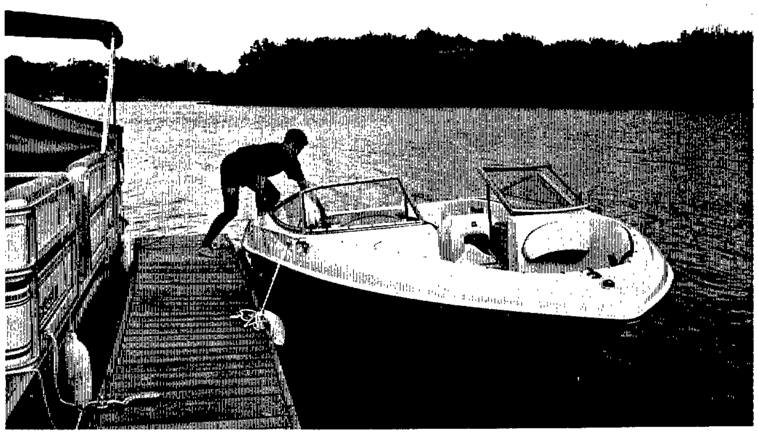

Photo A-24 Task K. Ingress/Egress Stern Step 4

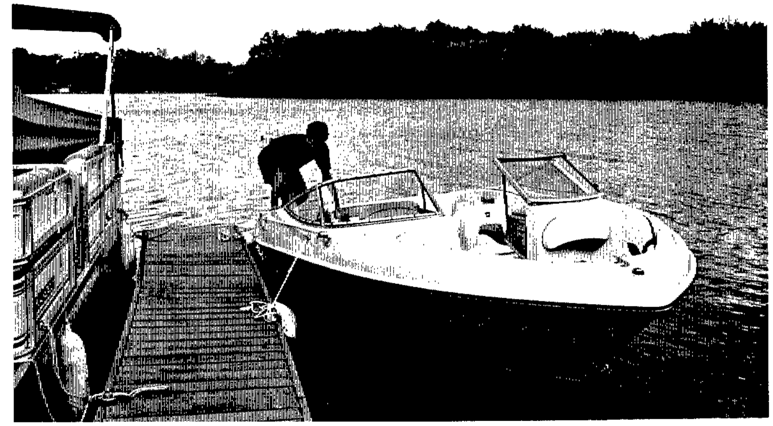

Photo A-25 Task K. Ingress/Egress Stern Step 5

Photo A-25 Task K. Ingress/Egress Stern Step 6

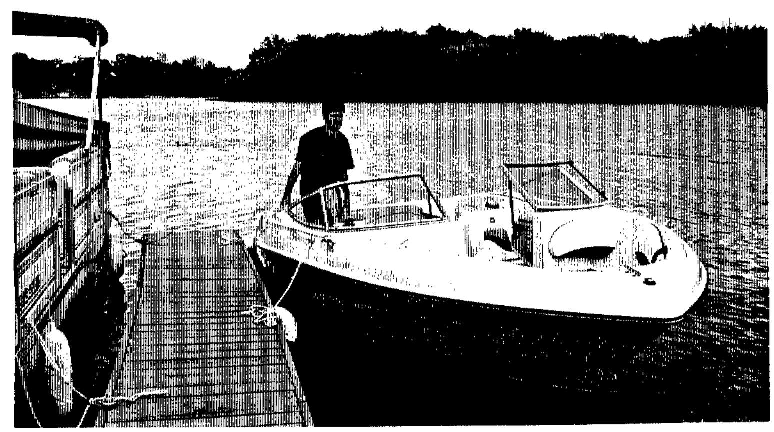

Photo A-27 Task K. Ingress/Egress Stern Step 7

Photo A-28 Task L. Stabilization Stern Seat

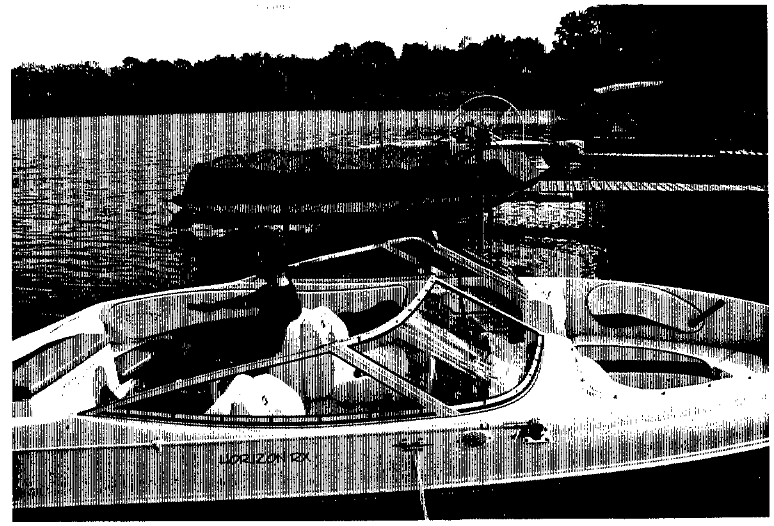

Photo A-29 Task L. Stabilization
Aft Facing Back-to-Back Seat

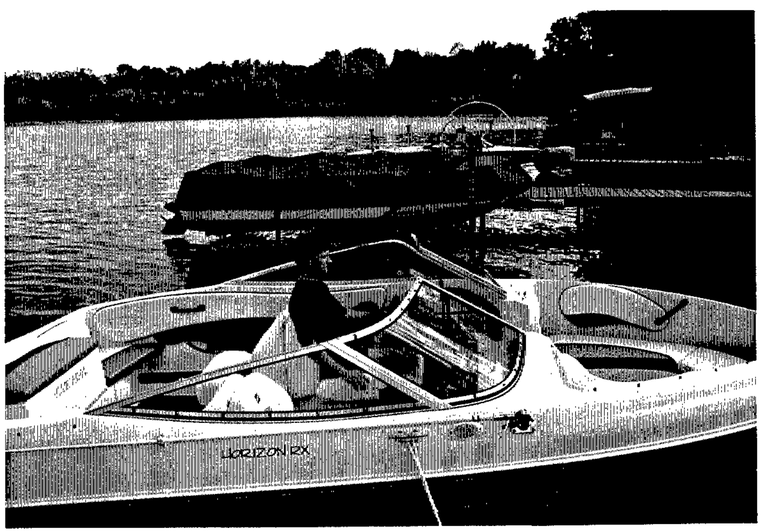

Photo A-30 Task L. Stabilization Seat Opposite Helm

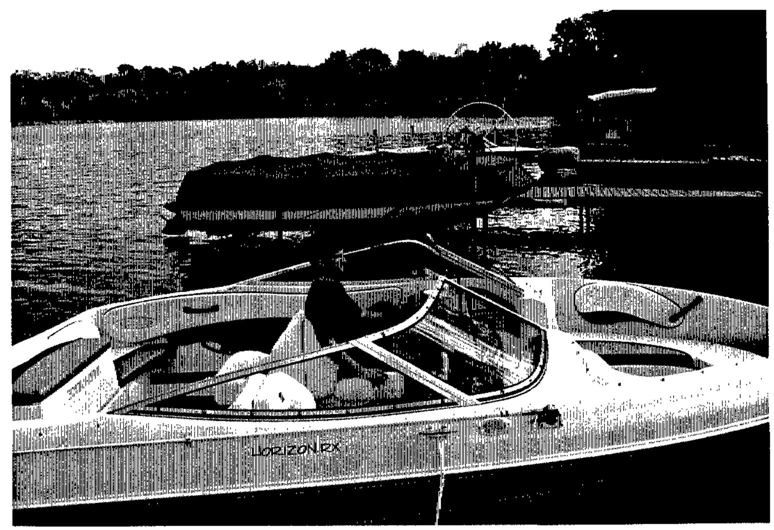

Photo A-31 Task L. Stabilization
Seat Opposite Helm (Trial 2)

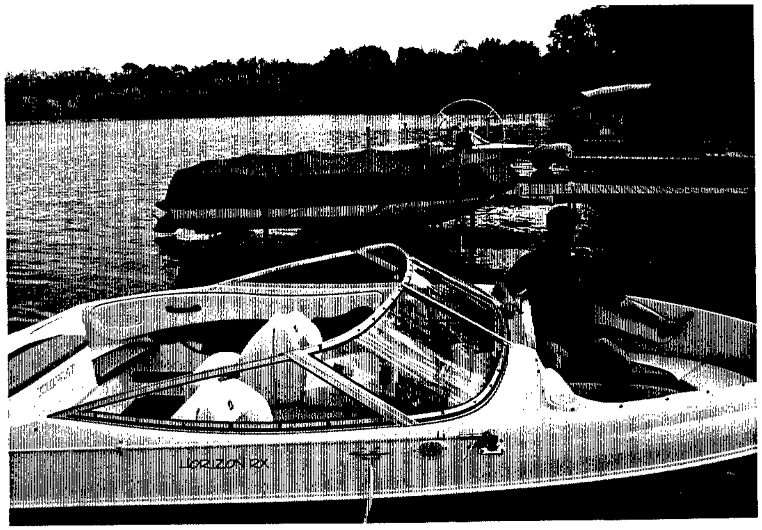

Photo A-32 Task I. Stabilization Bow Seat

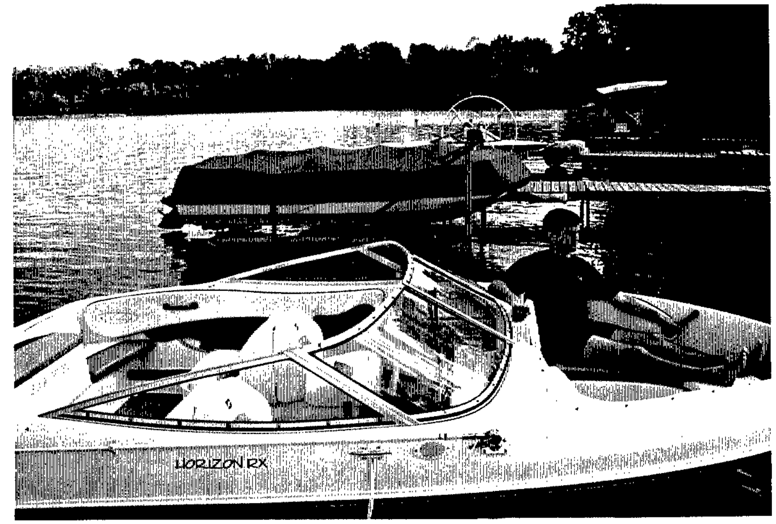

Photo A-33 Task I. Stabilization Bow Seat (Trial 2)

Photo A-34 Task A. Maneuvering
Cockpit to Bow Seating Area Step 1

Photo A-35 Task A. Maneuvering
Cockpit to Bow Seating Area Step 2

Photo A-36 Task A. Maneuvering
Cockpit to Bow Seating Area Step 3

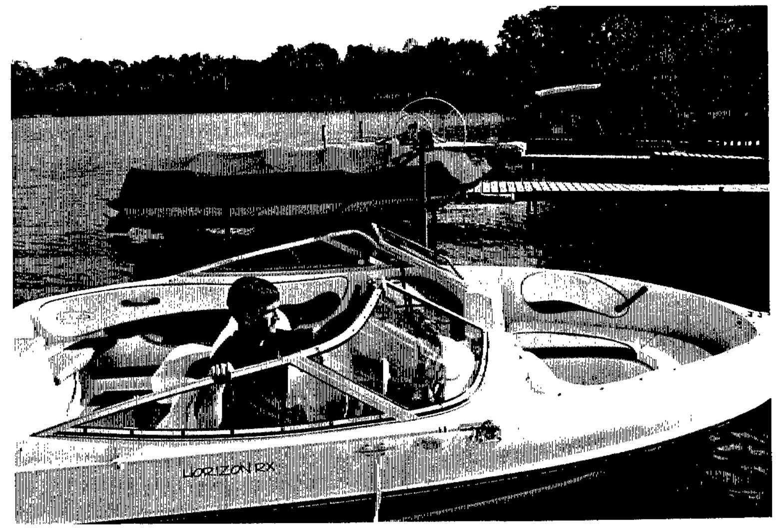

Photo B-0 Task A. Maneuvering
Cockpit to Bow Seating Area Step 4

Photo B-1 Task A. Maneuvering
Cockpit to Bow Seating Area Step 5

Photo B-2 Task A. Maneuvering
Cockpit to Bow Seating Area Step 6

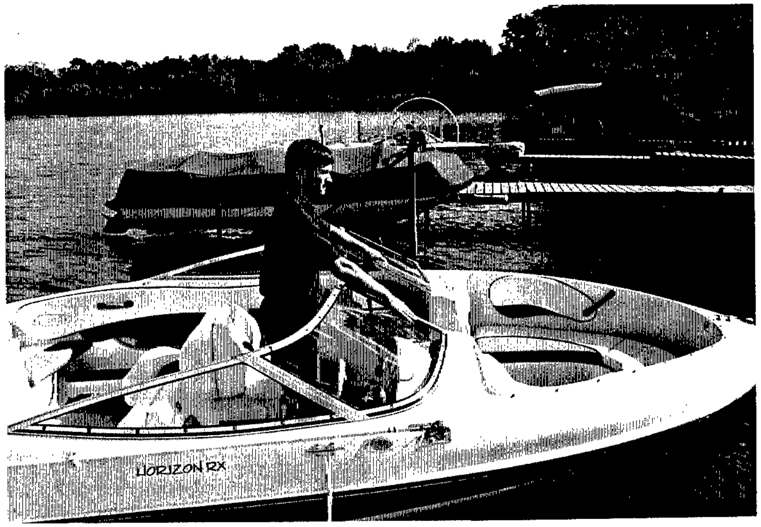

Photo B-3 Task A. Maneuvering
Cockpit to Bow Seating Area Step 7

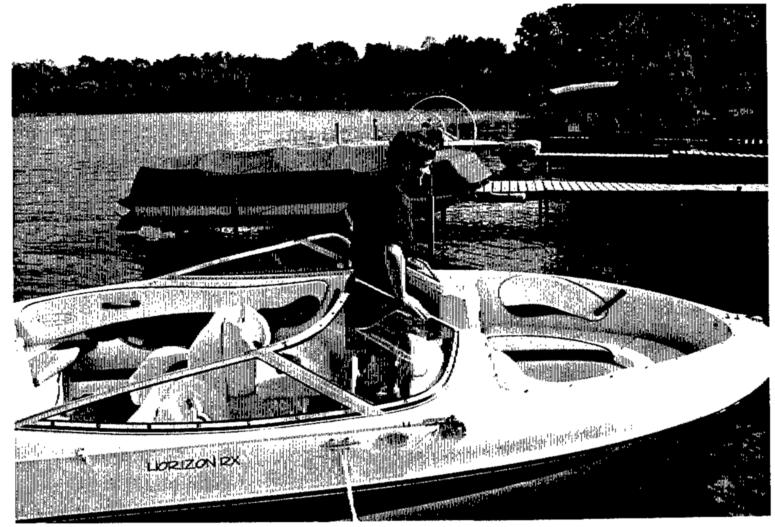

Photo B-4 Task A. Maneuvering
Cockpit to Bow Seating Area Step 8

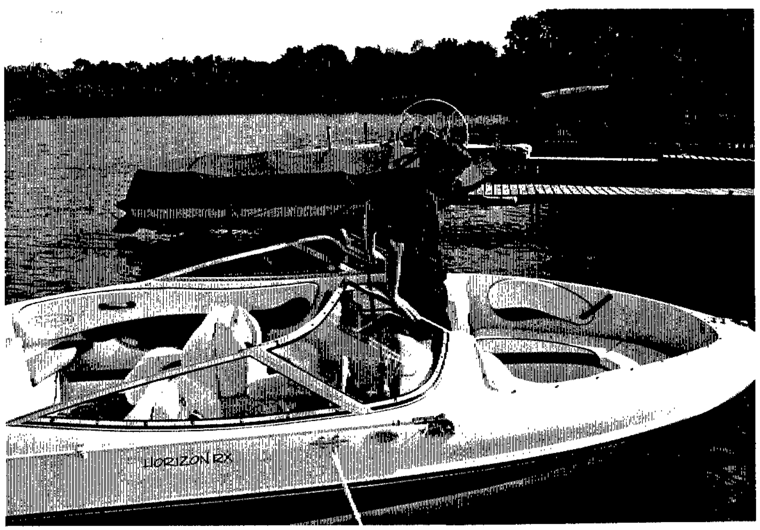

Photo B-5 Task A. Maneuvering
Cockpit to Bow Seating Area Step 9

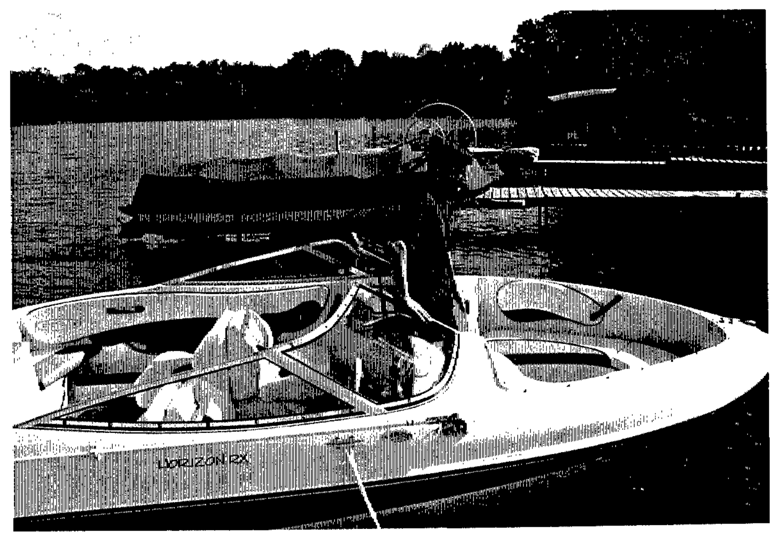

Photo B-6 Task A. Maneuvering
Cockpit to Bow Seating Area Step 10

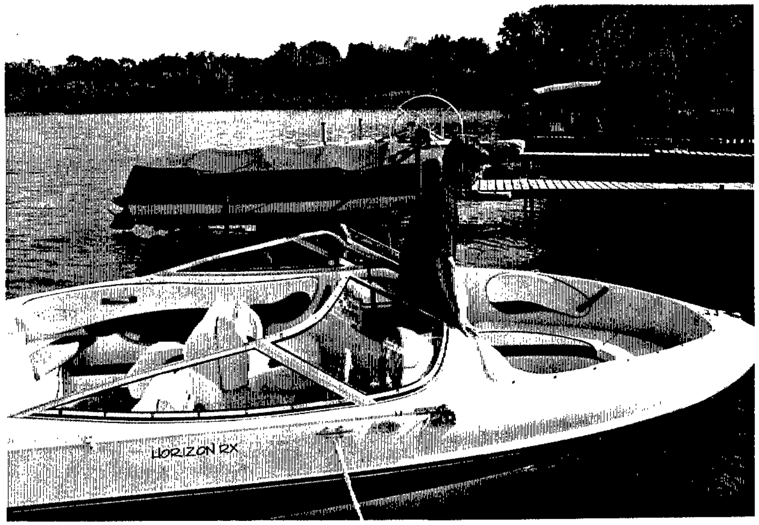

Photo B-7 Task A. Maneuvering
Cockpit to Bow Seating Area Step 11

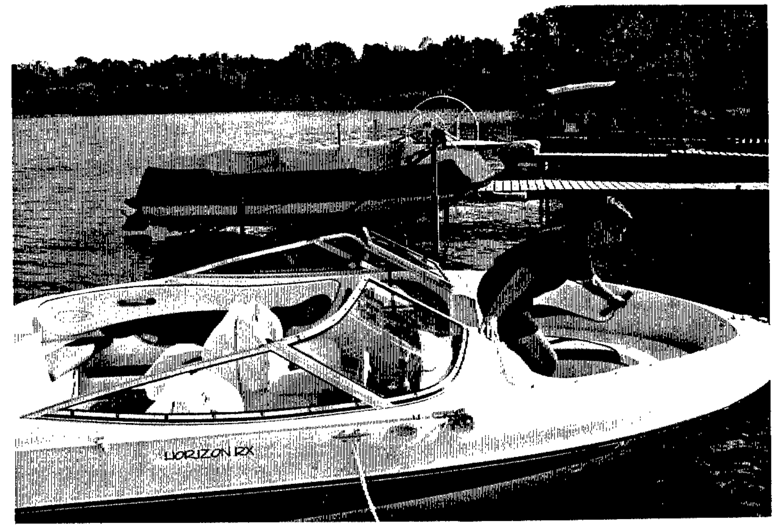

Photo B-8 Task A. Maneuvering
Cockpit to Bow Seating Area Step 12

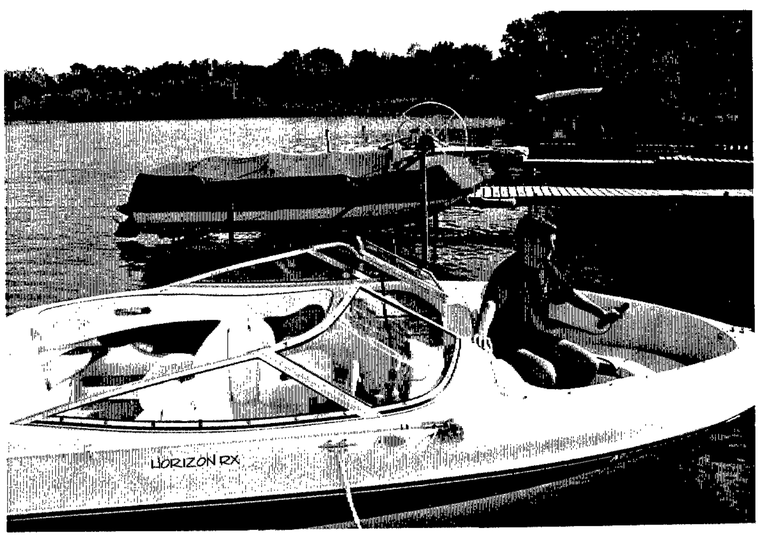

Photo B-9 Task A. Maneuvering
Cockpit to Bow Seating Area Step 13

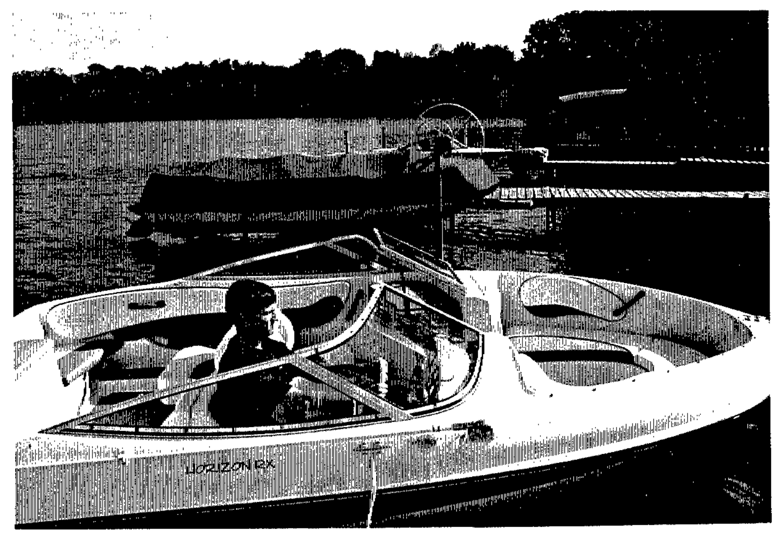

Photo B-10 Task D. Maneuvering about Cockpit
Fore to Aft Step 1

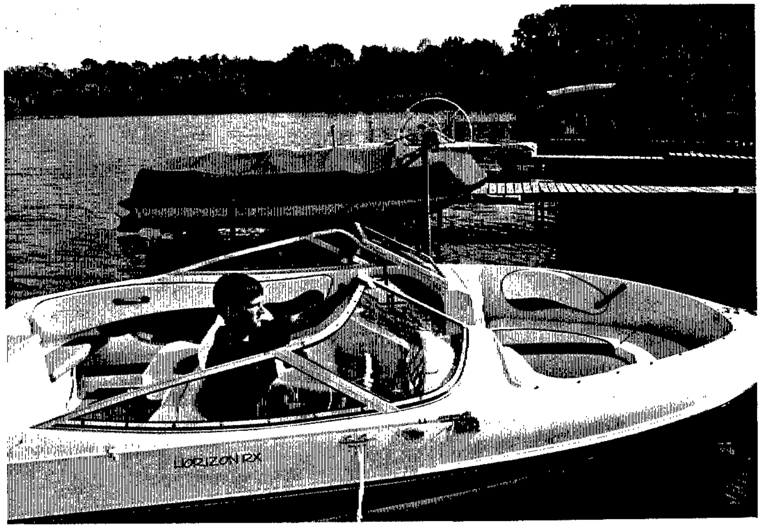

Photo B-11 Task D. Maneuvering about Cockpit
Fore to Aft Step 2

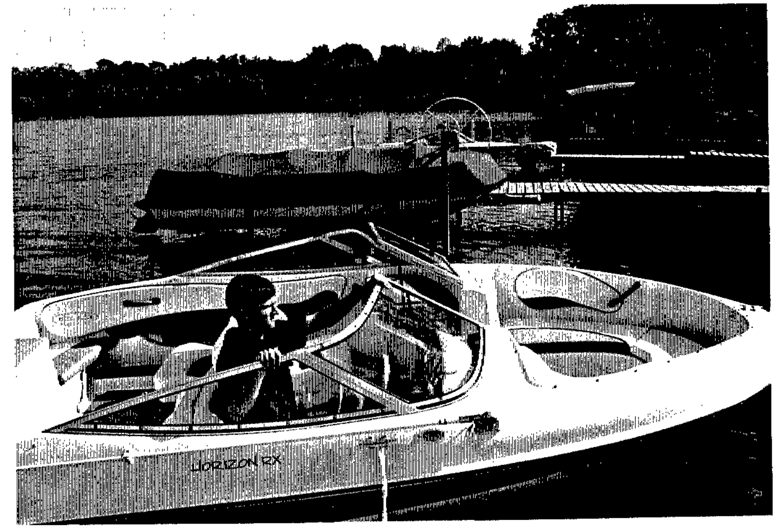

Photo B-12 Task D. Maneuvering about Cockpit
Fore to Aft Step 3

Photo B-13 Task D. Maneuvering about Cockpit
Fore to Aft Step 4

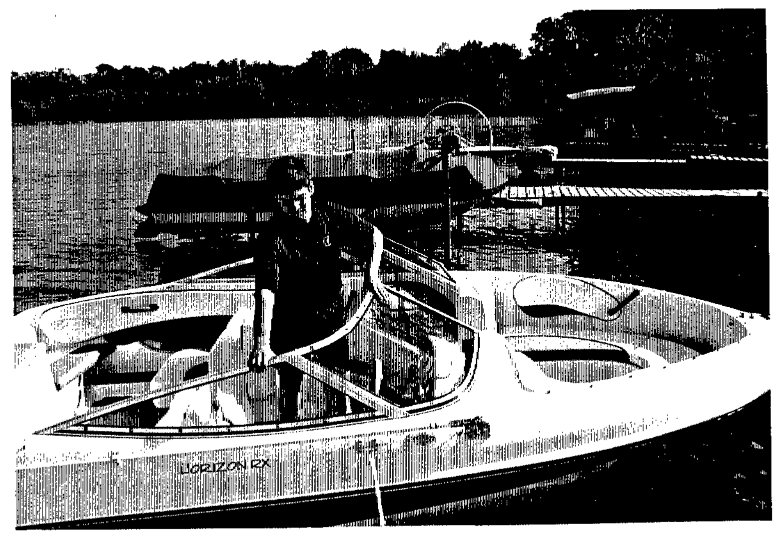

Photo B-14 Task D. Maneuvering about Cockpit
Fore to Aft Step 5

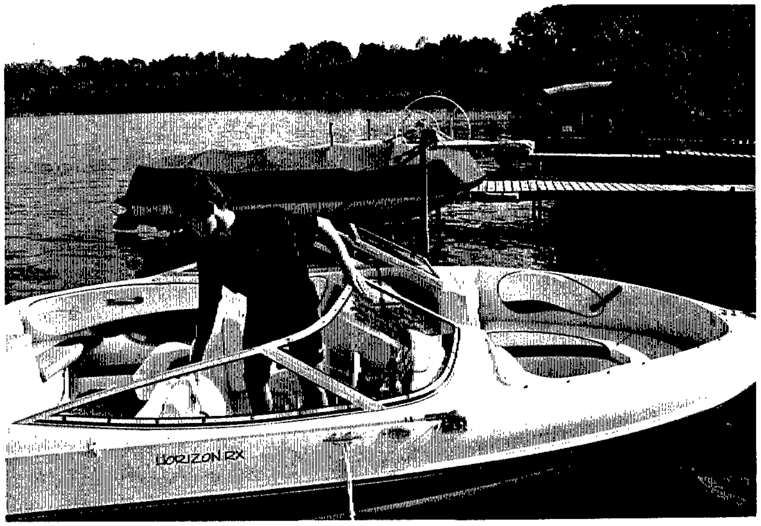

Photo B-15 Task D. Maneuvering about Cockpit
Fore to Aft Step 6

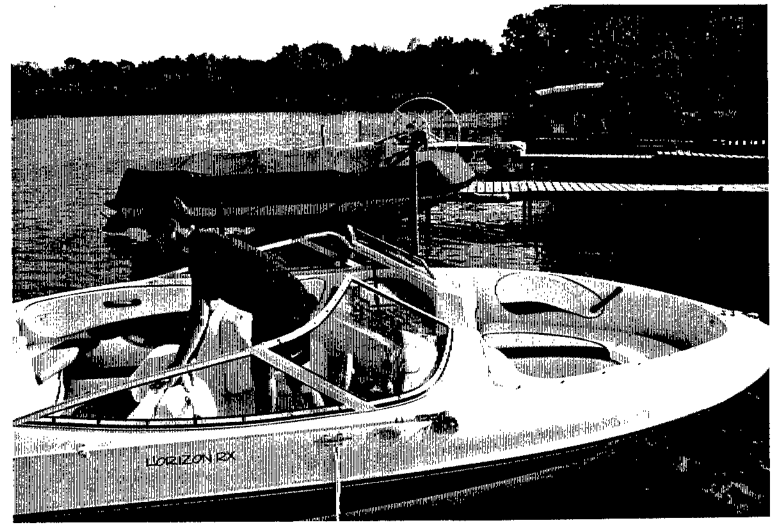

Photo B-16 Task D. Maneuvering about Cockpit
Fore to Aft Step 7

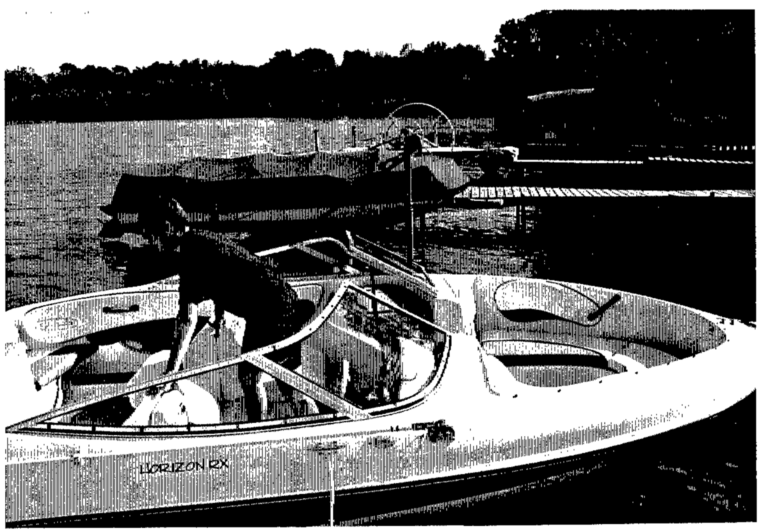

Photo B-17 Task D. Maneuvering about Cockpit
Fore to Aft Step 8

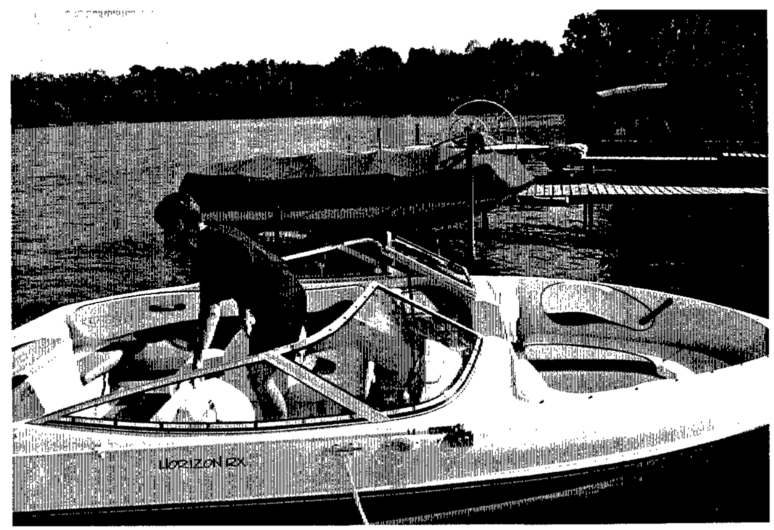

Photo B-20 Task D. Maneuvering about Cockpit
Fore to Aft Step 9

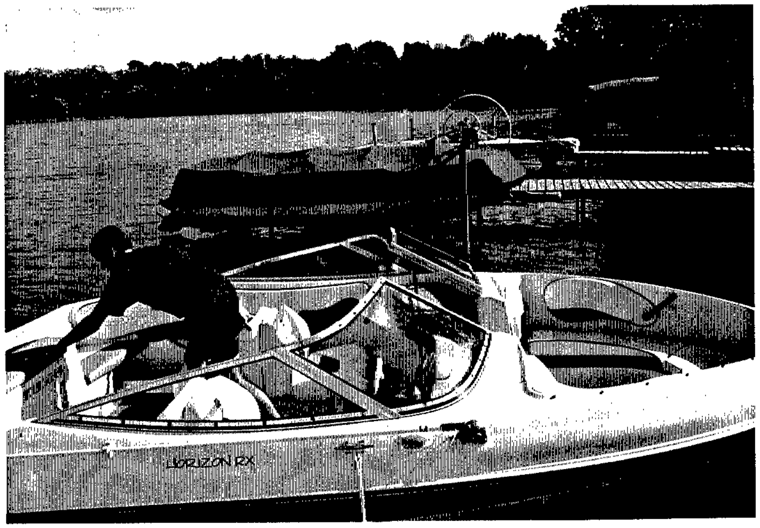

Photo B-21 Task D. Maneuvering about Cockpit
Fore to Aft Step 10

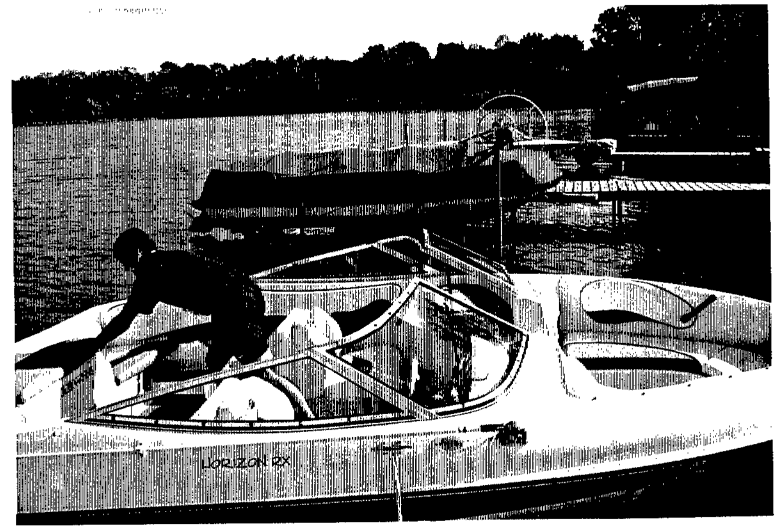

Photo B-22 Task D. Maneuvering about Cockpit
Fore to Aft Step 11

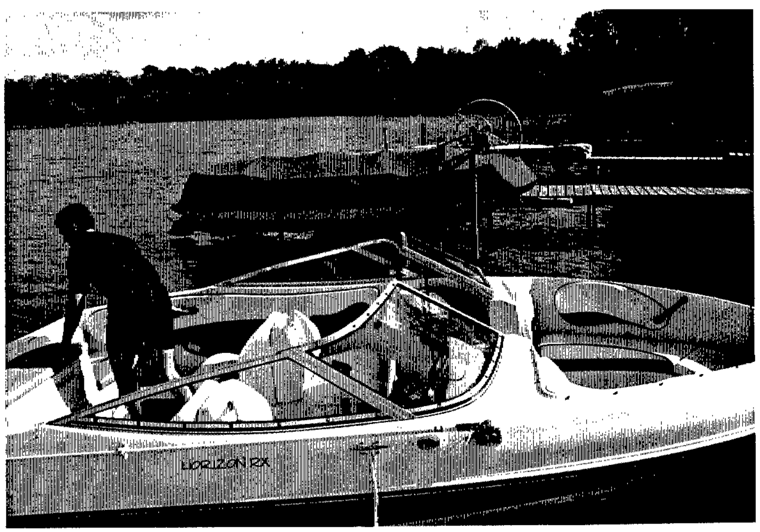

Photo B-23 Task D. Maneuvering about Cockpit
Fore to Aft Step 12

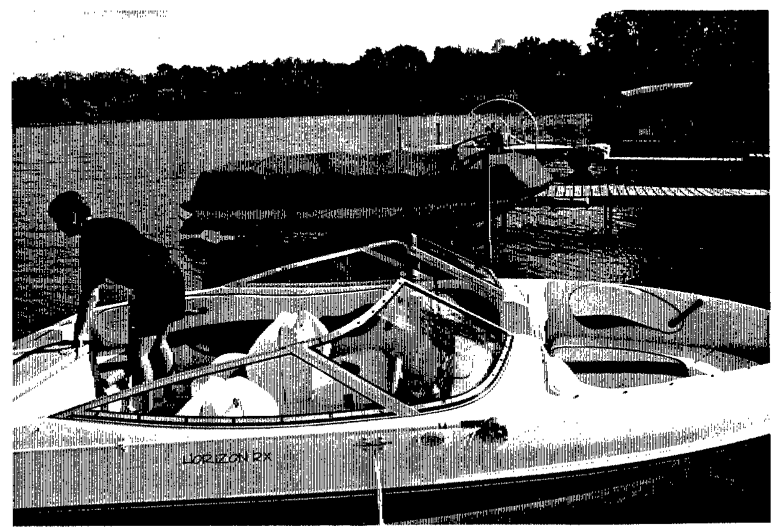

Photo B-24 Task D. Maneuvering about Cockpit
Fore to Aft Step 13

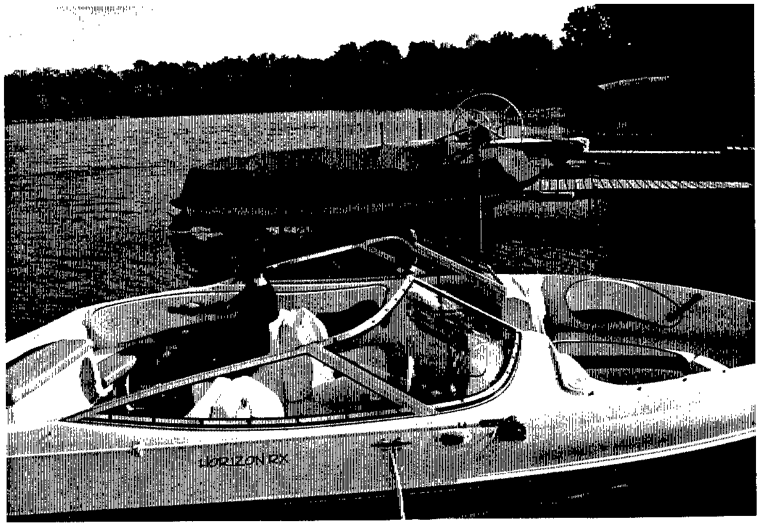

Photo B-25 Task E. Maneuvering about Cockpit Port to Starboard Step 1

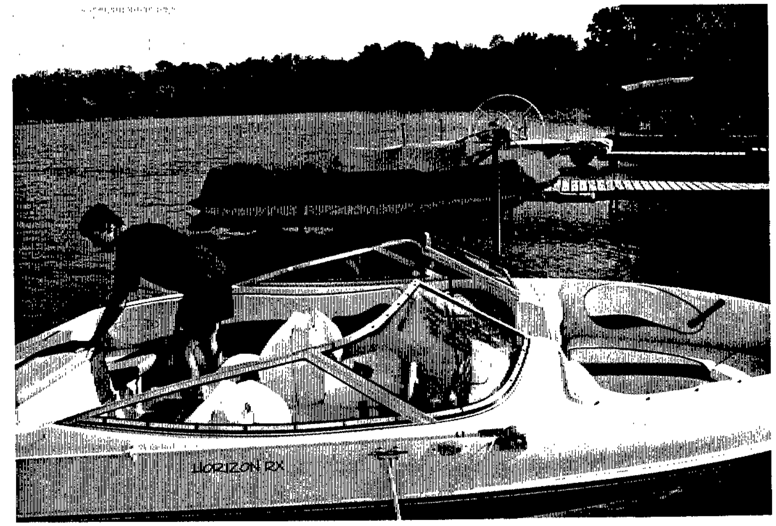

Photo B-26 Task E. Maneuvering about Cockpit Port to Starboard Step 2

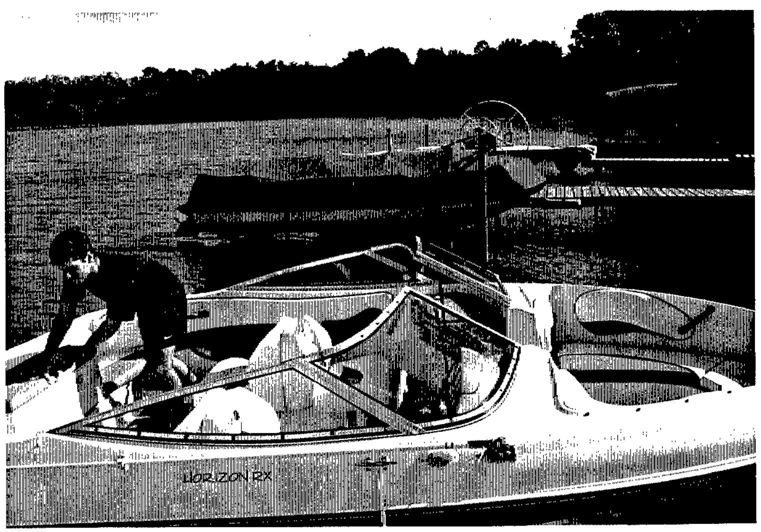

Photo B-27 Task E. Maneuvering about Cockpit Port to Starboard Step 3

Photo B-28 Task E. Maneuvering about Cockpit Port to Starboard Step 4

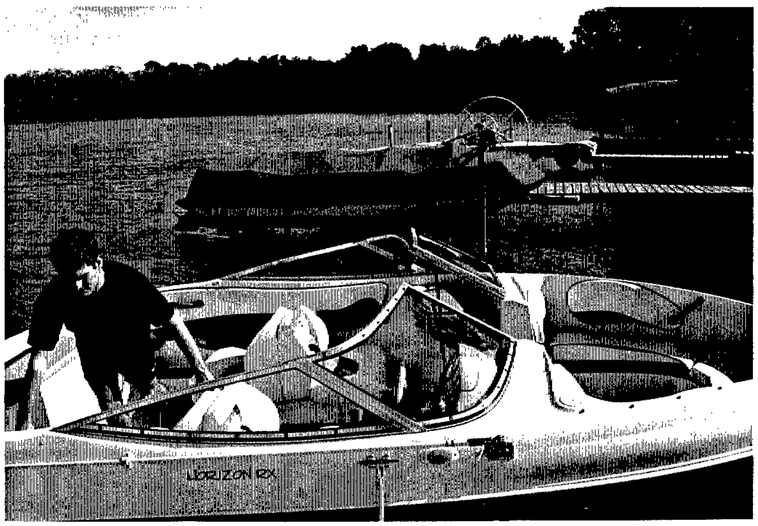

Photo B-29 Task E. Maneuvering about Cockpit Port to Starboard Step 5

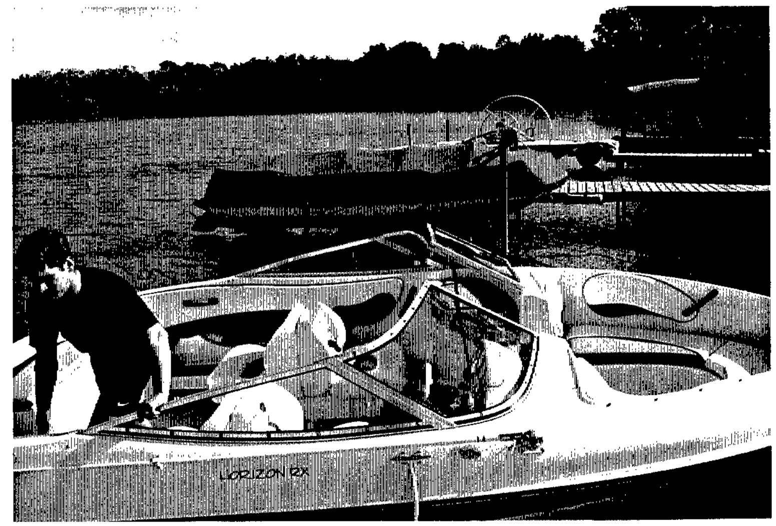

Photo B-30 Task E. Maneuvering about Cockpit Port to Starboard Step 6

Photo B-31 Task E. Maneuvering about Cockpit Port to Starboard Step 7

Photo B-32 Task E. Maneuvering about Cockpit Port to Starboard Step 8

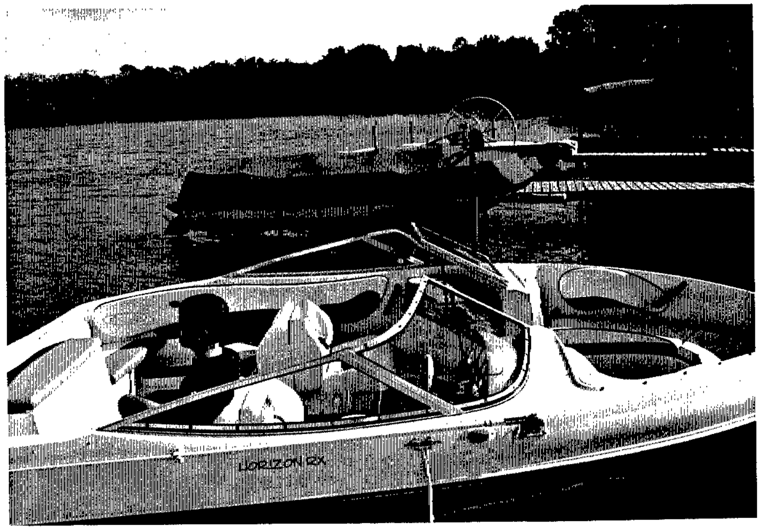

Photo B-33 Task E. Maneuvering about Cockpit
Port to Starboard Step 9

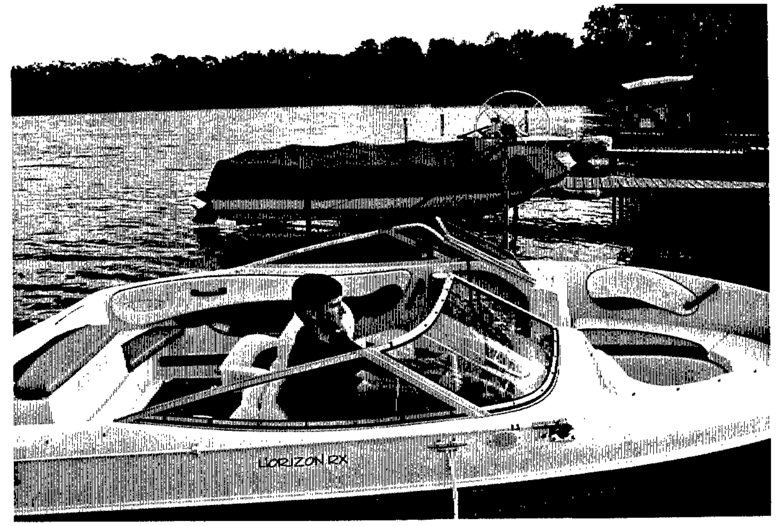

Photo C-0 Task E. Maneuvering about Cockpit
Starboard to Port Step 1

Photo C-1 Task E. Maneuvering about Cockpit
Starboard to Port Step 2

Photo C-2 Task E. Maneuvering about Cockpit
Starboard to Port Step 3

Photo C-3 Task E. Maneuvering about Cockpit
Starboard to Port Step 4

Photo C-4 Task E. Maneuvering about Cockpit
Starboard to Port Step 5

Photo C-5 Task E. Maneuvering about Cockpit
Starboard to Port Step 6

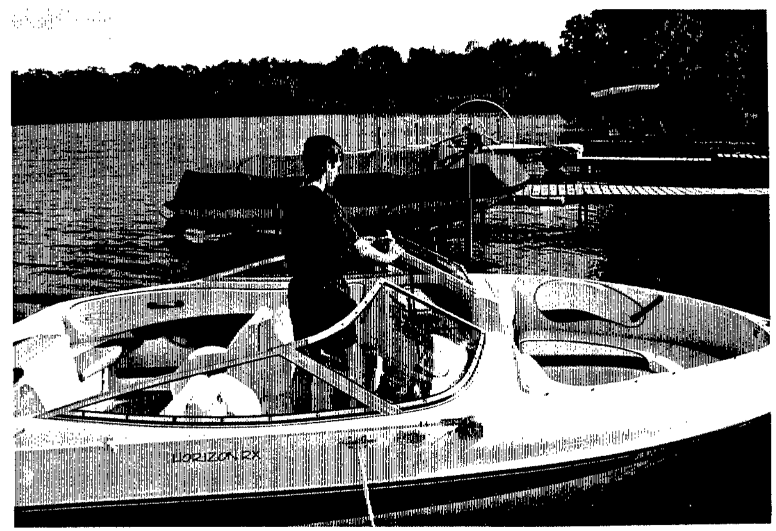

Photo C-6 Task E. Maneuvering about Cockpit
Starboard to Port Step 7

Photo C-7 Task E. Maneuvering about Cockpit Starboard to Port Step 8

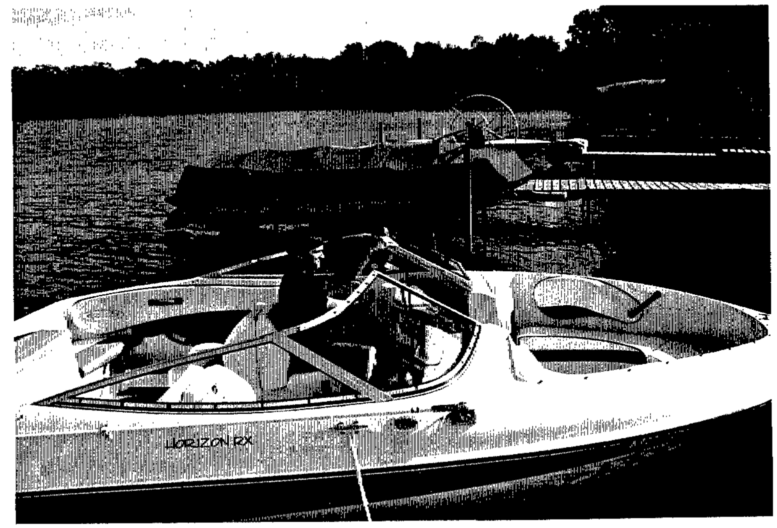

Photo C-8 Task E. Maneuvering about Cockpit Starboard to Port Step 9

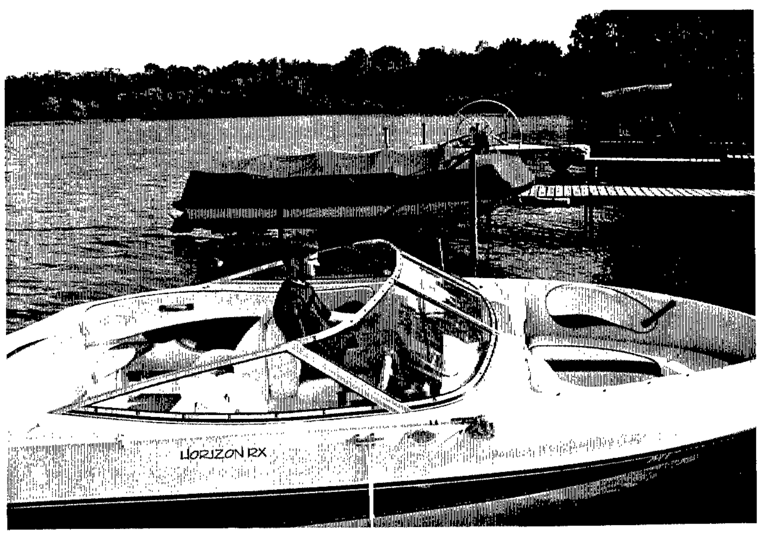

Photo C-9 Task E. Maneuvering about Cockpit Starboard to Port Step 10

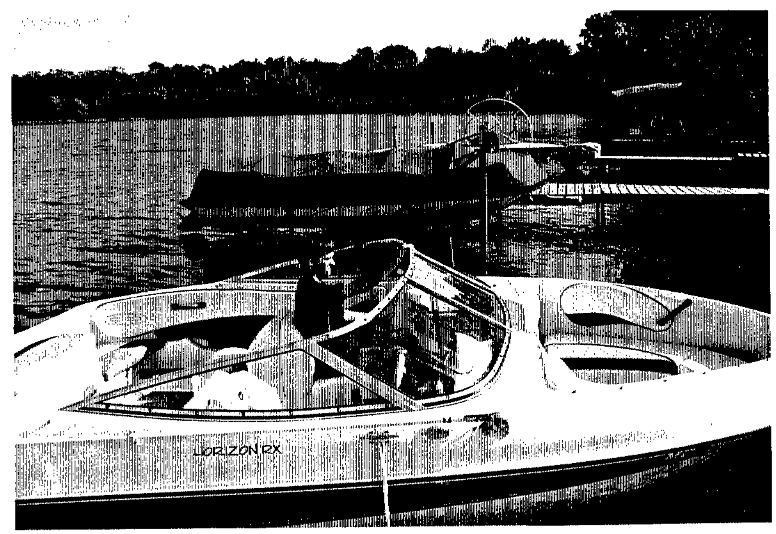

Photo C-10 Task E. Maneuvering about Cockpit Port to Starboard Step 1

Photo C-11 Task E. Maneuvering about Cockpit
Port to Starboard Step 2

Photo C-12 Task E. Maneuvering about Cockpit
Port to Starboard Step 3

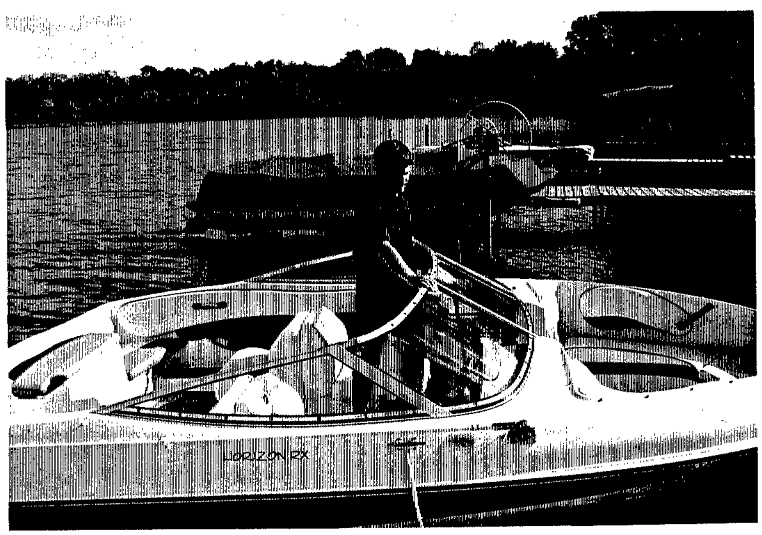

Photo C-13 Task E. Maneuvering about Cockpit
Port to Starboard Step 4

Photo C-14 Task E. Maneuvering about Cockpit
Port to Starboard Step 5

Photo C-15 Task E. Maneuvering about Cockpit
Port to Starboard Step 6

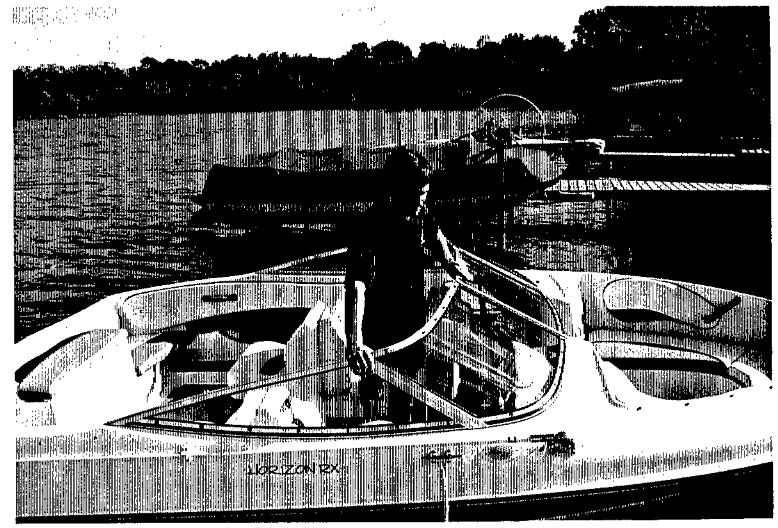

Photo C-16 Task E. Maneuvering abput Cockpit
Port to Starboard Step 7

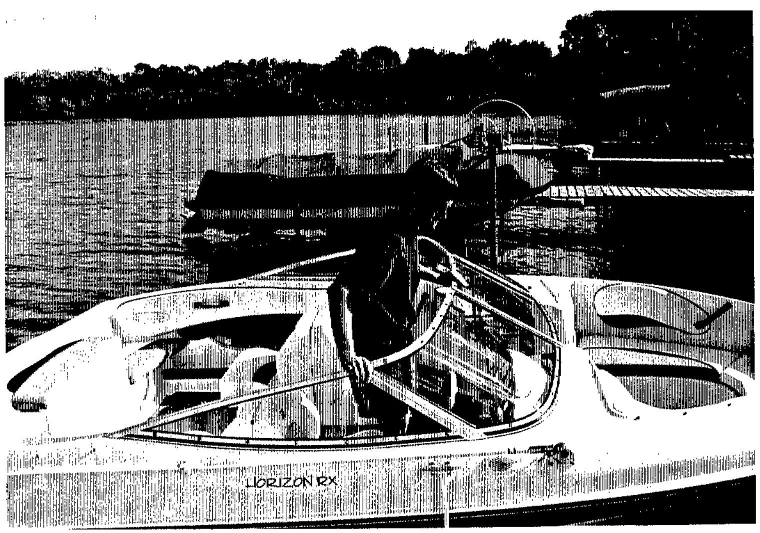

Photo C-17 Task E. Maneuvering about Cockpit
Port to Starboard Step 8

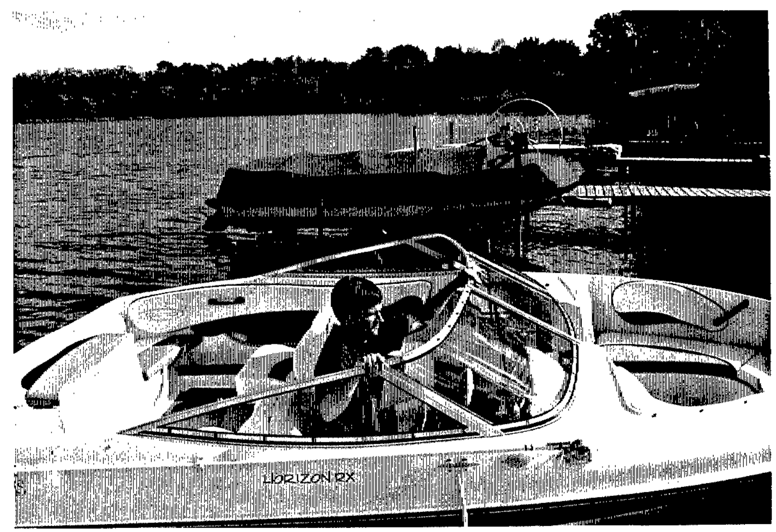

Photo C-18 Task E. Maneuvering about Cockpit
Port to Starboard Step 9

Photo C-19 Task E. Maneuvering about Cockpit
Port to Starboard Step 10

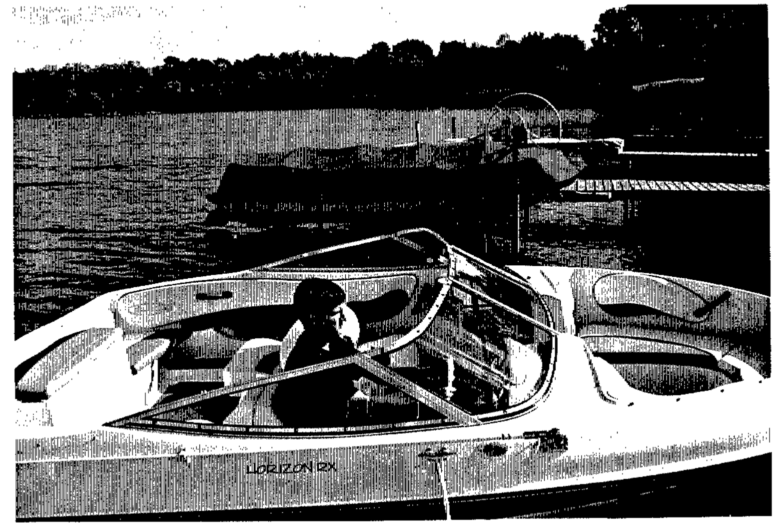

Photo C-20 Task E. Maneuvering about Cockpit
Port to Starboard Step 11

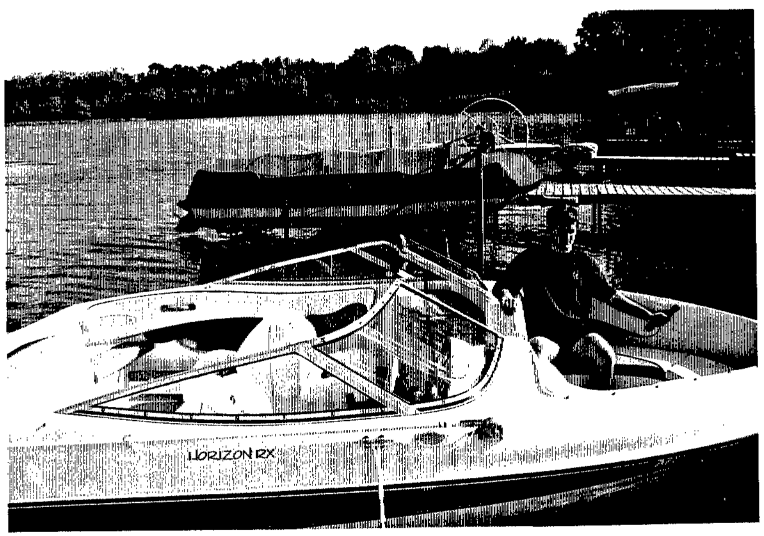

Photo C-21 Task A. Maneuvering
Bow Seating Area to Cockpit Step 1

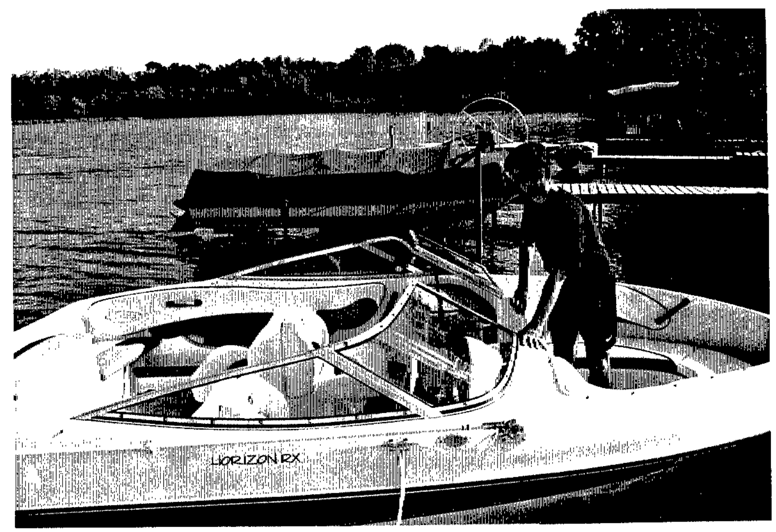

Photo C-22 Task A. Maneuvering
Bow Seating Area to Cockpit Step 2

Photo C-23 Task A. Maneuvering
Bow Seating Area to Cockpit Step 3

Photo C-24 Task A. Maneuvering
Bow Seating Area to Cockpit Step 4

Photo C-25 Task A. Maneuvering
Bow Seating Area to Cockpit Step 5

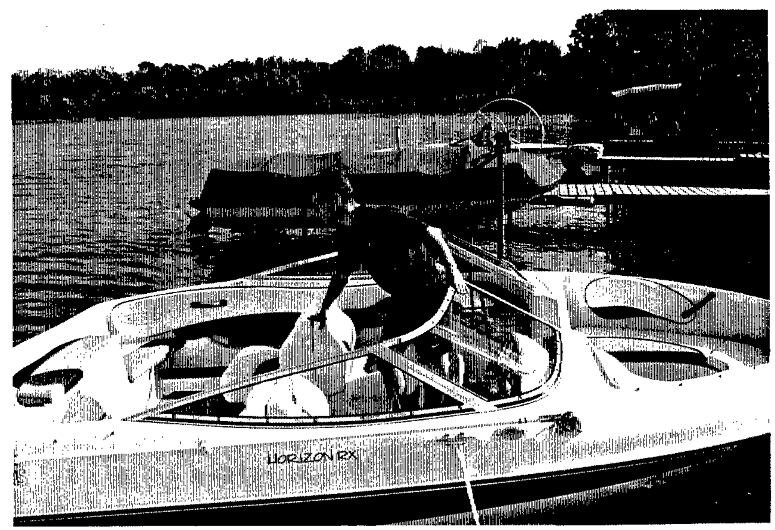

Photo C-26 Task A. Maneuvering
Bow Seating Area to Cockpit Step 6

Photo C-27 Task A. Maneuvering
Bow Seating Area to Cockpit Step 7

Photo C-28 Task A. Maneuvering
Bow Seating Area to Cockpit Step 8

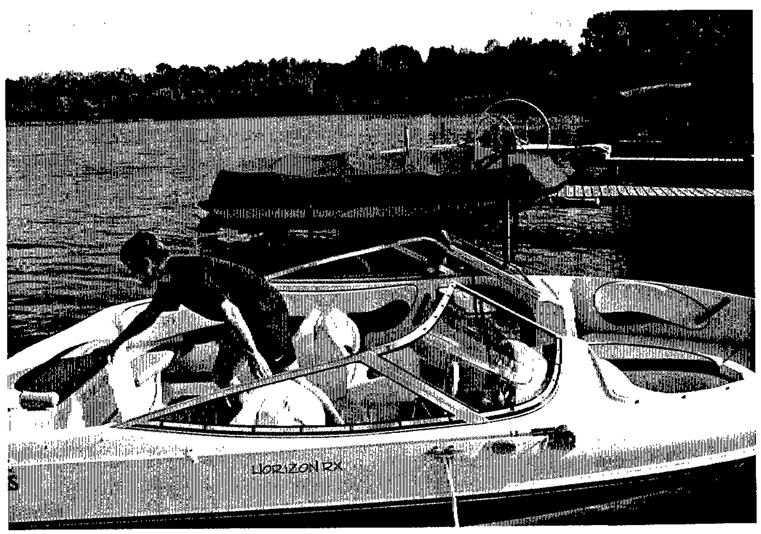

Photo C-29 Task A. Maneuvering
Bow Seating Area to Cockpit Step 9

Photo C-30 Task A. Maneuvering
Bow Seating Area to Cockpit Step 10

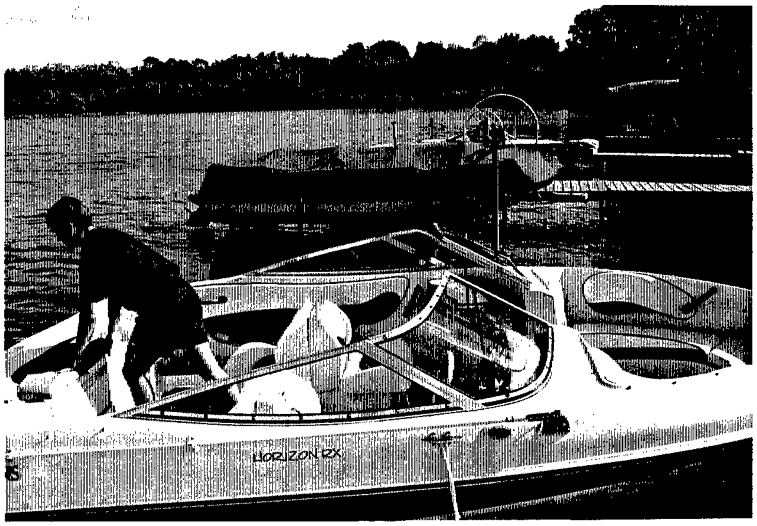

Photo C-31 Task A. Maneuvering
Bow Seating Area to Cockpit Step 11

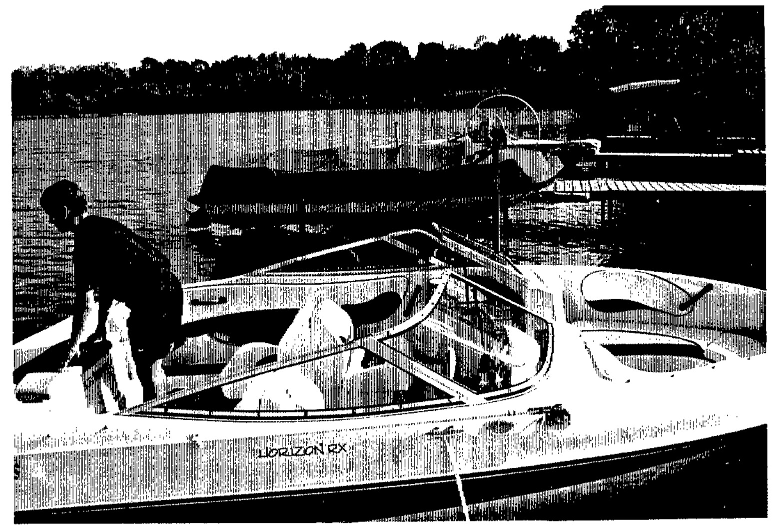

Photo C-32 Task A. Maneuvering
Bow Seating Area to Cockpit Step 12

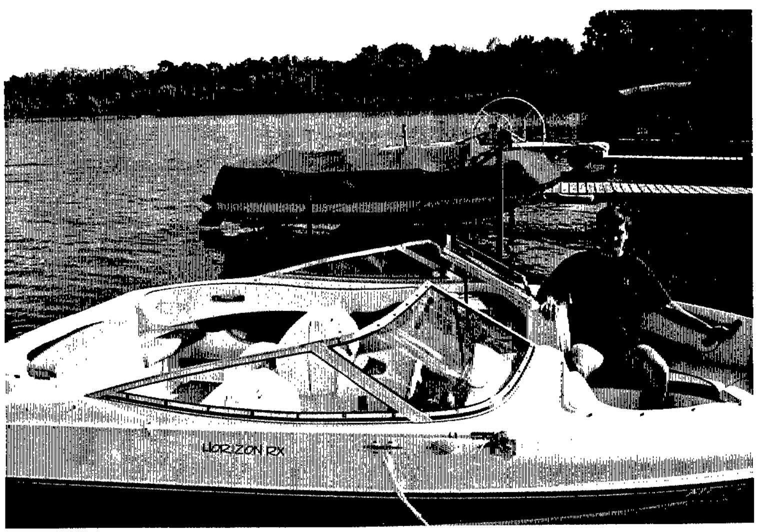

Photo C-33 Task A. Maneuvering
Bow Seating Area to Cockpit (Trial 2) Step 1

Photo C-34 Task A. Maneuvering
Bow Seating Area to Cockpit (Trial 2) Step 2

Photo C-35 Task A. Maneuvering
Bow Seating Area to Cockpit (Trial 2) Step 3

Photo D-0 Task A. Maneuvering
Bow Seating Area to Cockpit (Trial 2) Step 4

Photo D-1 Task A. Maneuvering
Bow Seating Area to Cockpit (Trial 2) Step 5

Photo D-2 Task A. Maneuvering
Bow Seating Area to Cockpit (Trial 2) Step 6

Photo D-3 Task A. Maneuvering
Bow Seating Area to Cockpit (Trial 2) Step 7

Photo D-4 Task A. Maneuvering
Bow Seating Area to Cockpit (Trial 2) Step 8

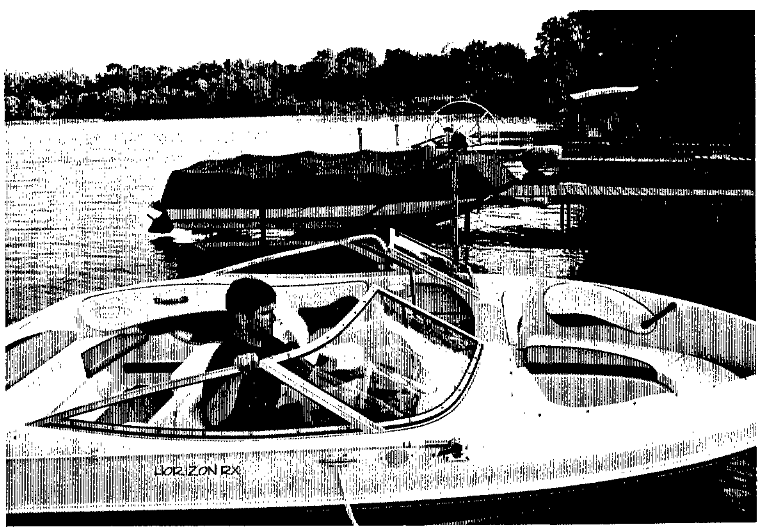

Photo D-5 Task A. Maneuvering
Bow Seating Area to Cockpit (Trial 2) Step 9

Photo D-6 Task A. Maneuvering
Bow Seating Area to Cockpit (Trial 2) Step 10

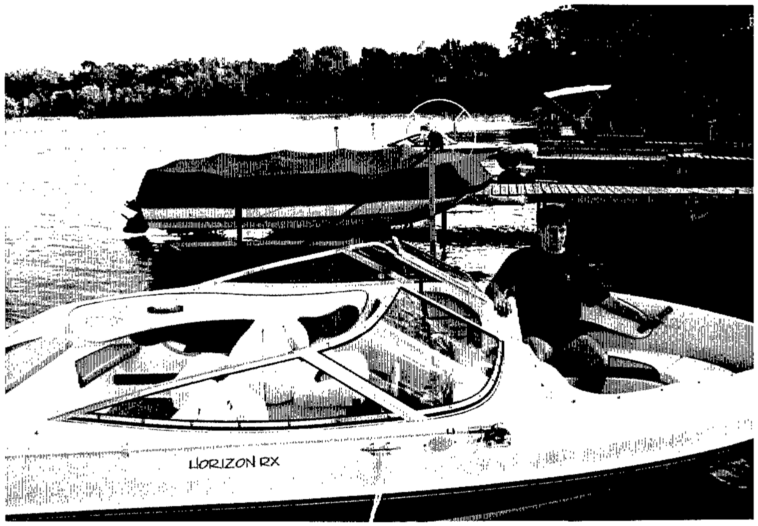

Photo D-7 Task H. Maneuvering about Bow
Port to Starboard Step 1

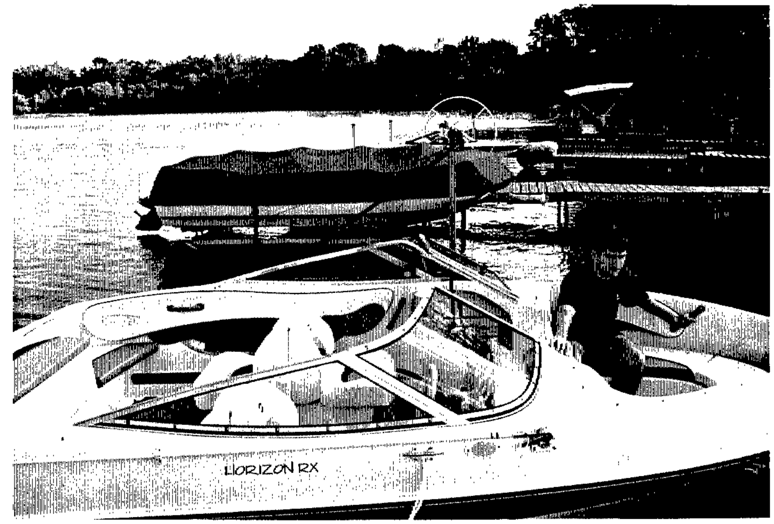

Photo D-8 Task H. Maneuvering about Bow
Port to Starboard Step 2

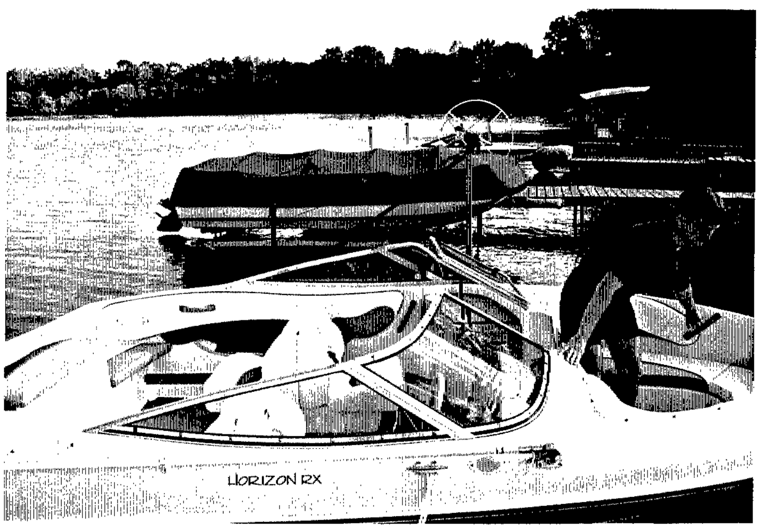

Photo D-9 Task H. Maneuvering about Bow
Port to Starboard Step 3

Photo D-10 Task H. Maneuvering about Bow
Port to Starboard Step 4

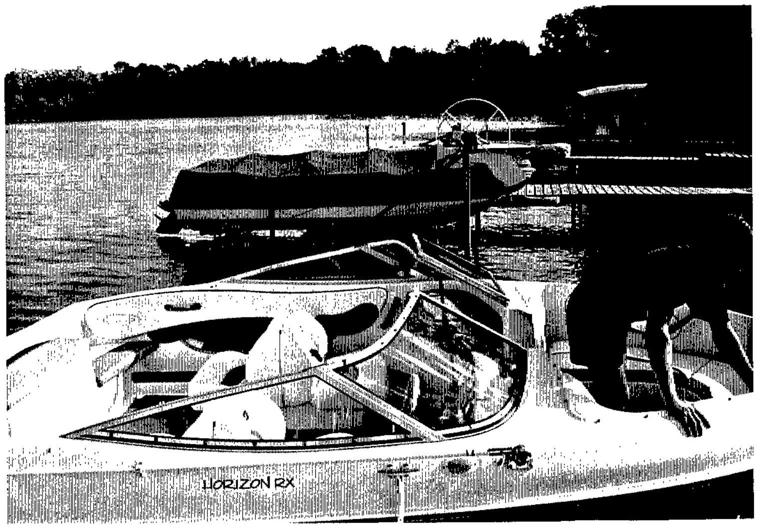

Photo D-11 Task H. Maneuvering about Bow
Port to Starboard Step 5

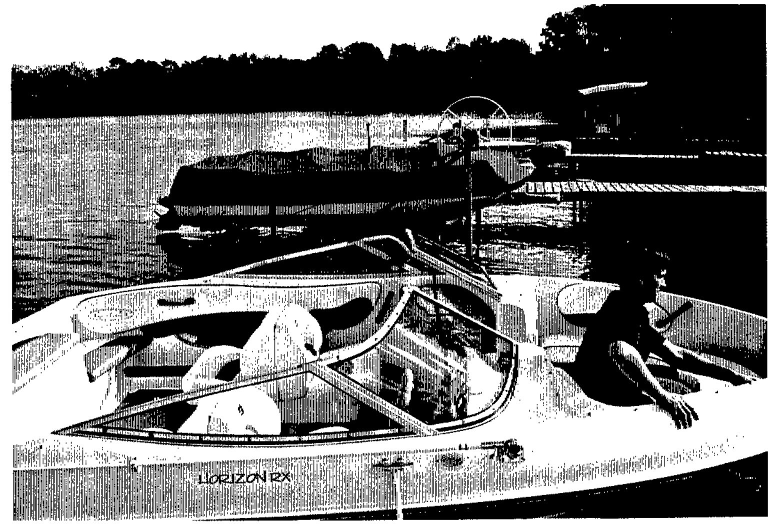

Photo D-12 Task H. Maneuvering about Bow
Port to Starboard Step 6

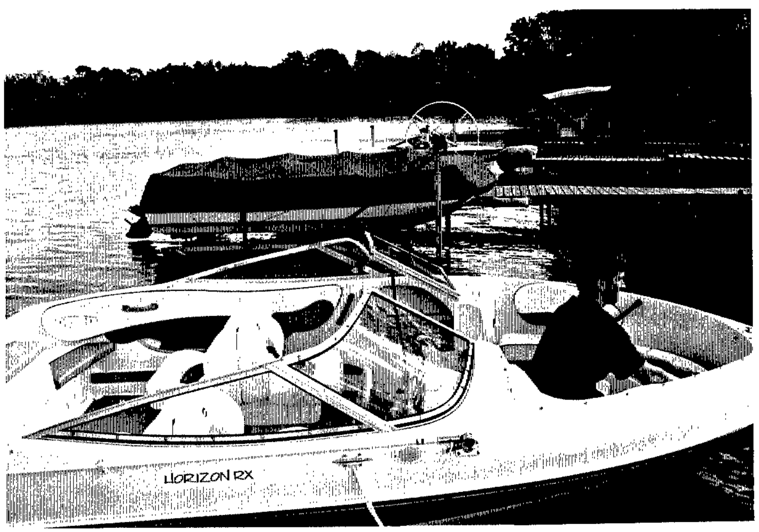

Photo D-13 Task H. Maneuvering about Bow
Port to Starboard Step 7

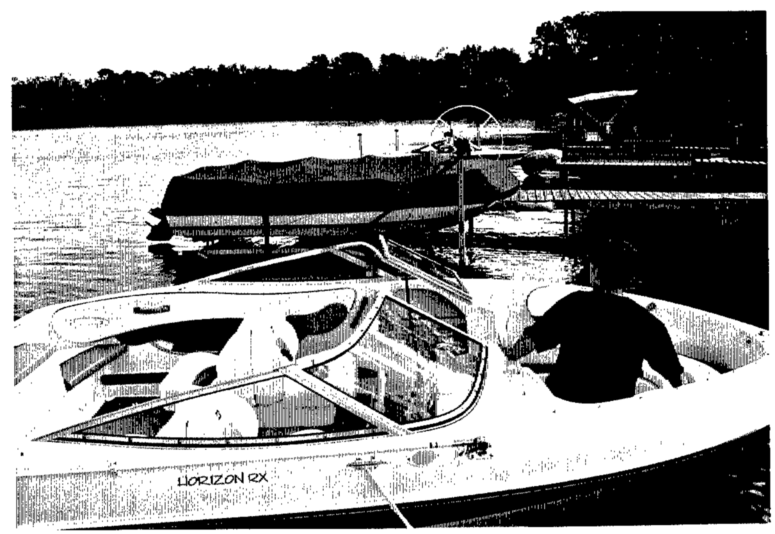

Photo D-14 Task H. Maneuvering about Bow
Port to Starboard Step 8

Photo D-15 Task H. Maneuvering about Bow
Port to Starboard Step 9

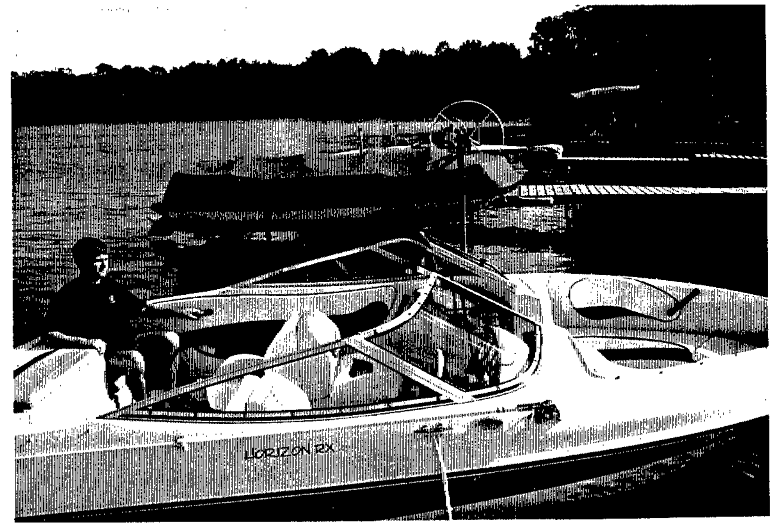

Photo D-16 Task E. Maneuvering about Cockpit
Port to Starboard Step 1

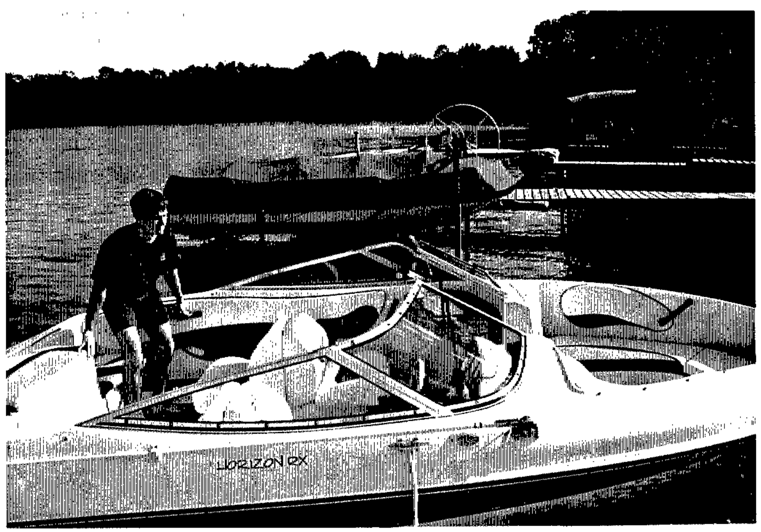

Photo D-17 Task E. Maneuvering about Cockpit
Port to Starboard Step 2

Photo D-18 Task E. Maneuvering about Cockpit
Port to Starboard Step 3

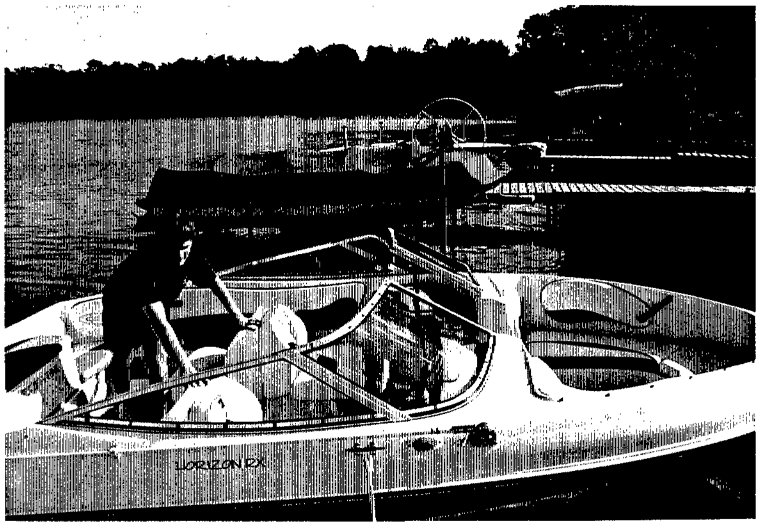

Photo D-19 Task E. Maneuvering about Cockpit
Port to Starboard Step 4

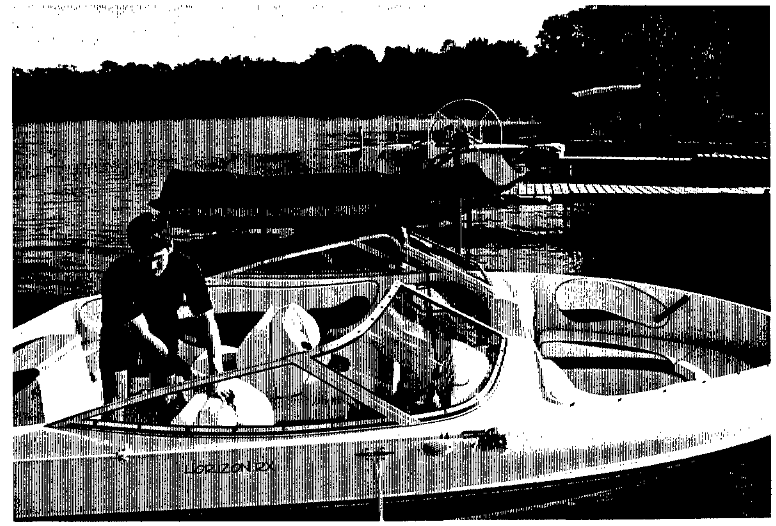

Photo D-20 Task E. Maneuvering about Cockpit
Port to Starboard Step 5

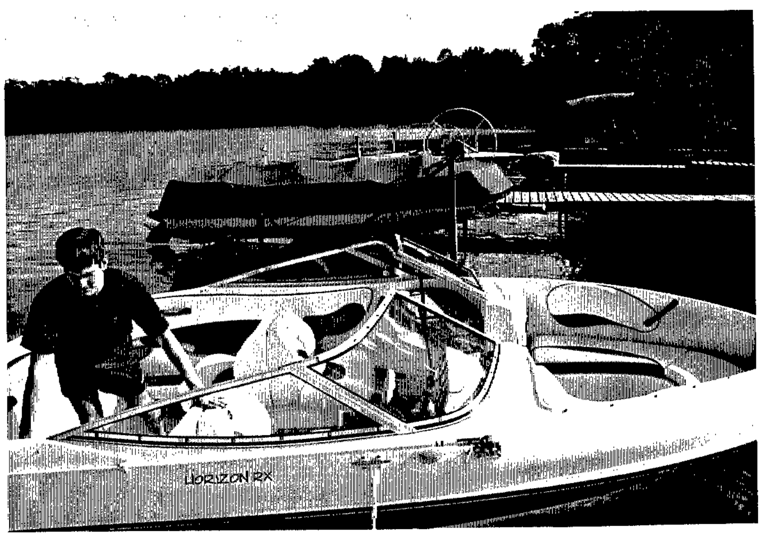

Photo D-21 Task E. Maneuvering about Cockpit
Port to Starboard Step 6

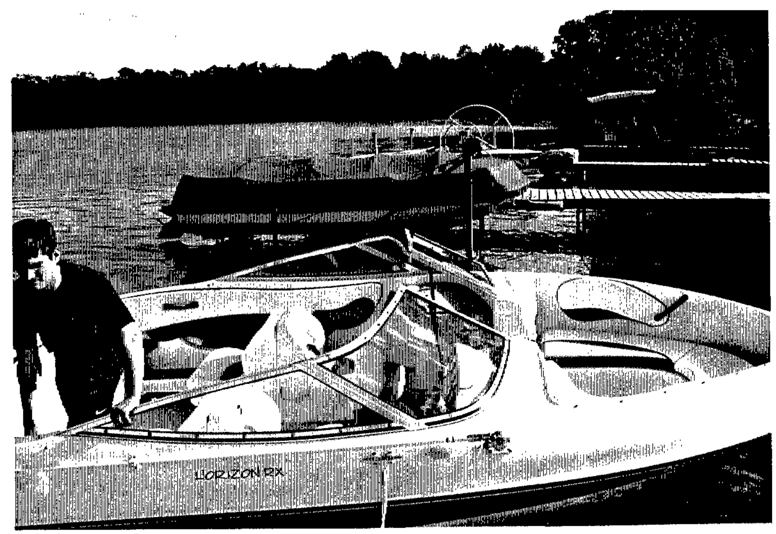

Photo D-22 Task E. Maneuvering about Cockpit
Port to Starboard Step 7

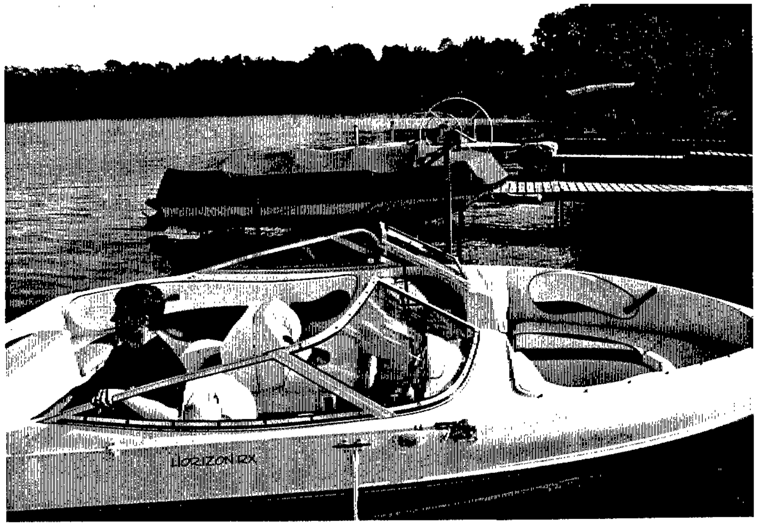

Photo D-23 Task E. Maneuvering about Cockpit
Port to Starboard Step 8

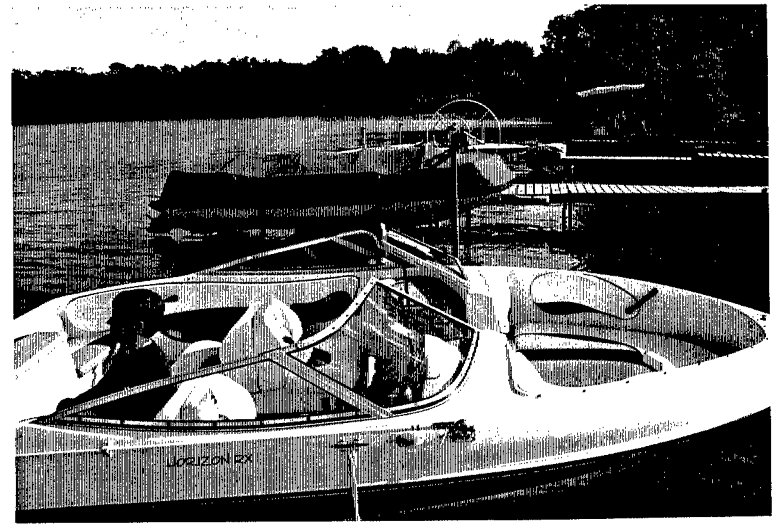

Photo D-24 Task E. Maneuvering about Cockpit
Port to Starboard Step 9

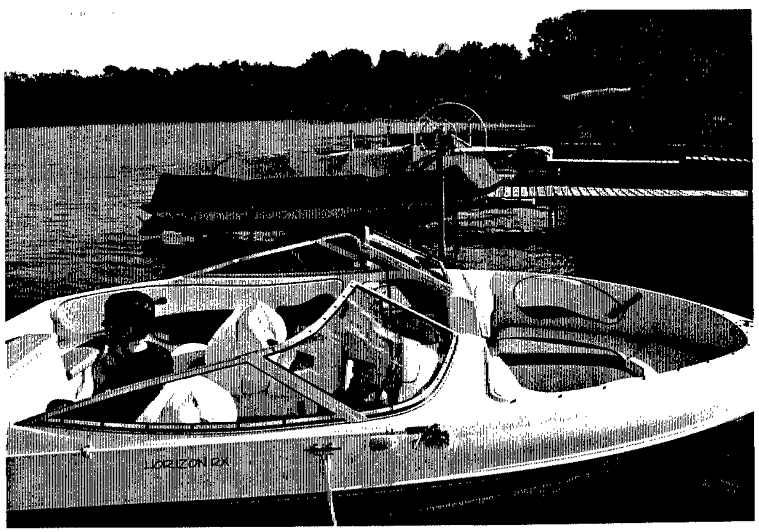

Photo D-25 Task E. Maneuvering about Cockpit
Port to Starboard Step 10

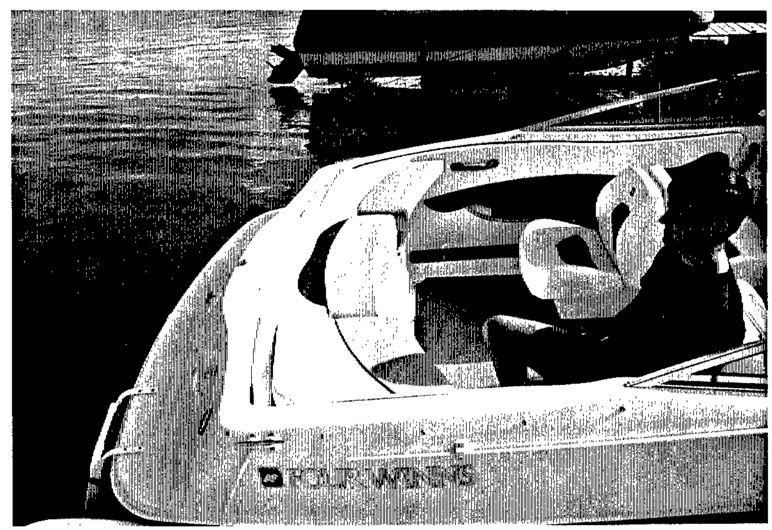

Photo D-26 Task E. Transitioning
Cockpit to Sundeck to Swim Platform Step 1

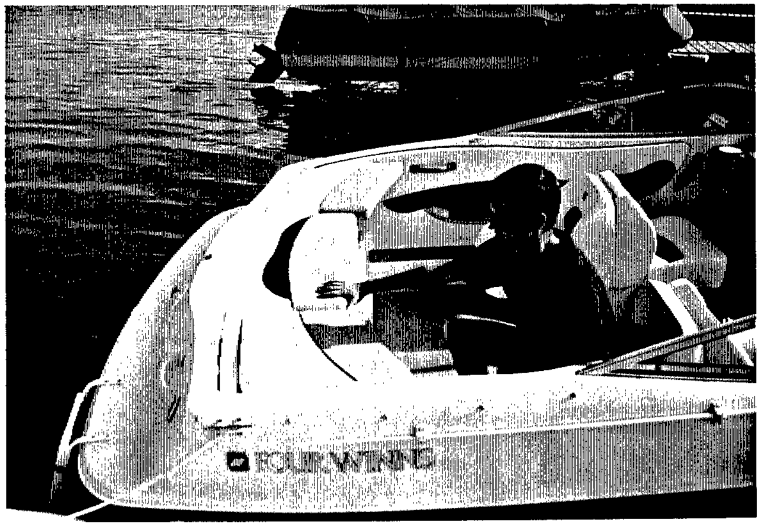

Photo E-1 Task E. Transitioning
Cockpit to Sundeck to Swim Platform Step 2

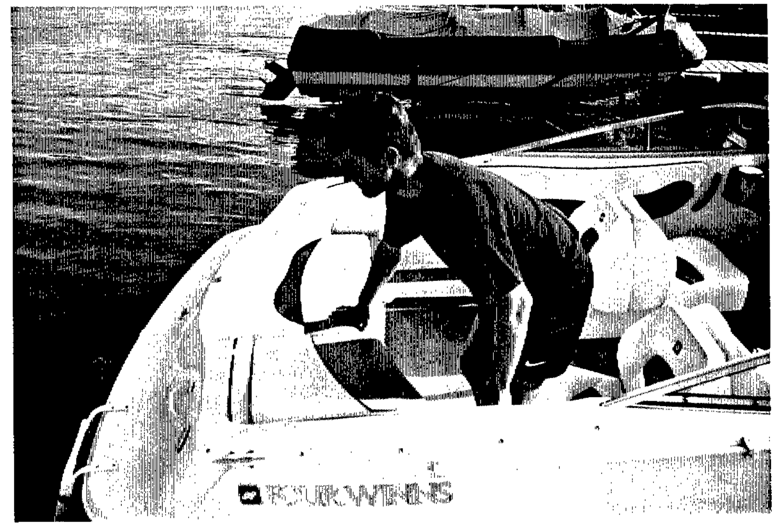

Photo E-2 Task E. Transitioning
Cockpit to Sundeck to Swim Platform Step 3

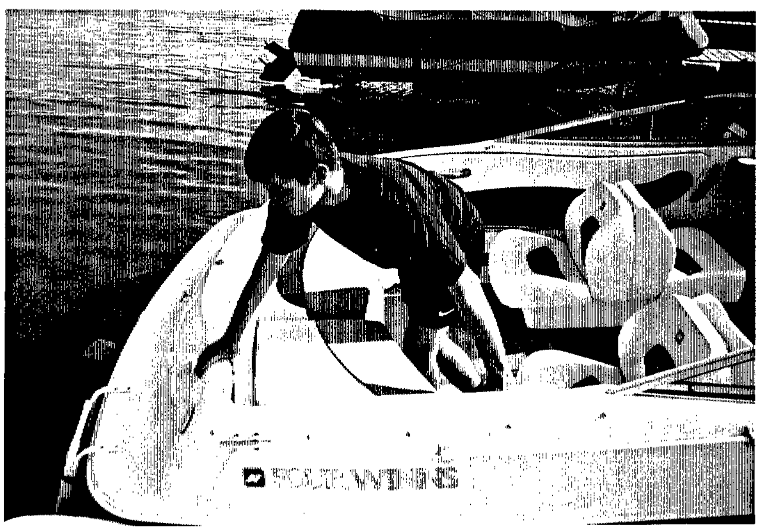

Photo E-3 Task E. Transitioning
Cockpit to Sundeck to Swim Platform Step 4

Photo E-4 Task E. Transitioning
Cockpit to Sundeck to Swim Platform Step 5

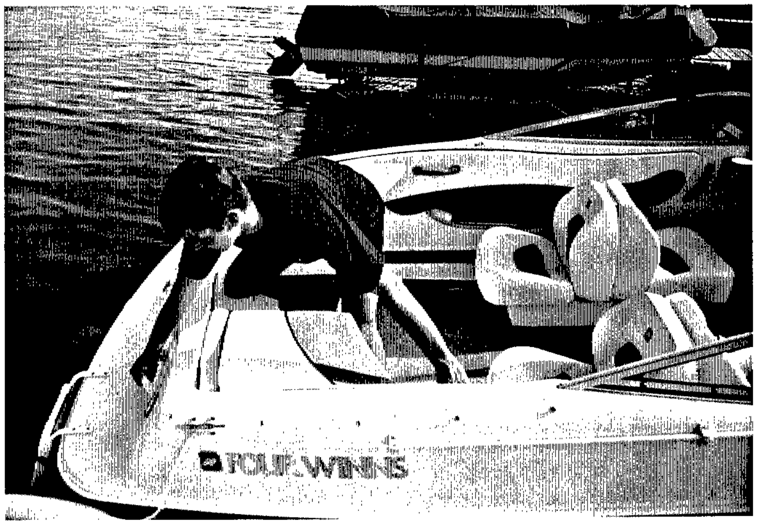

Photo E-5 Task E. Transitioning
Cockpit to Sundeck to Swim Platform Step 6

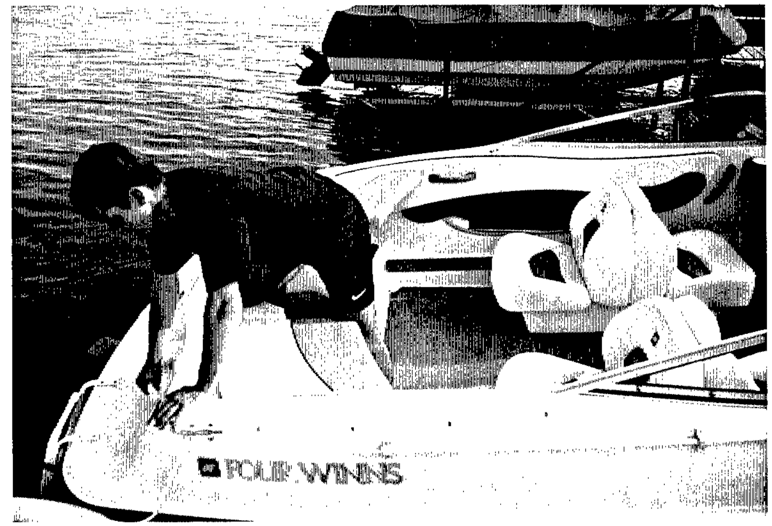

Photo E-6 Task E. Transitioning
Cockpit to Sundeck to Swim Platform Step 7

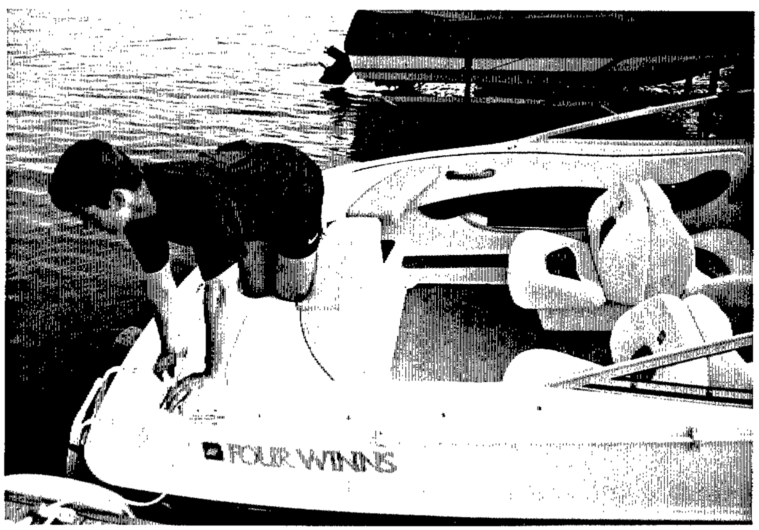

Photo E-7 Task E. Transitioning
Cockpit to Sundeck to Swim Platform Step 8

Photo E-8 Task E. Transitioning
Cockpit to Sundeck to Swim Platform Step 9

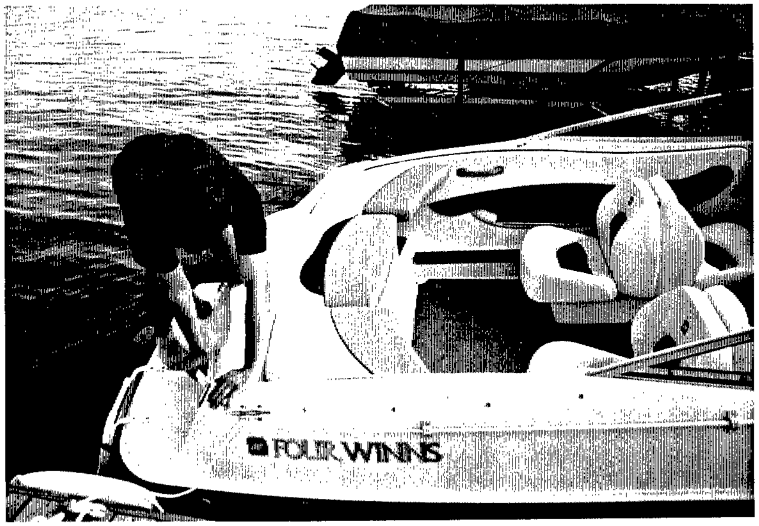

Photo E-9 Task E. Transitioning
Cockpit to Sundeck to Swim Platform Step 10

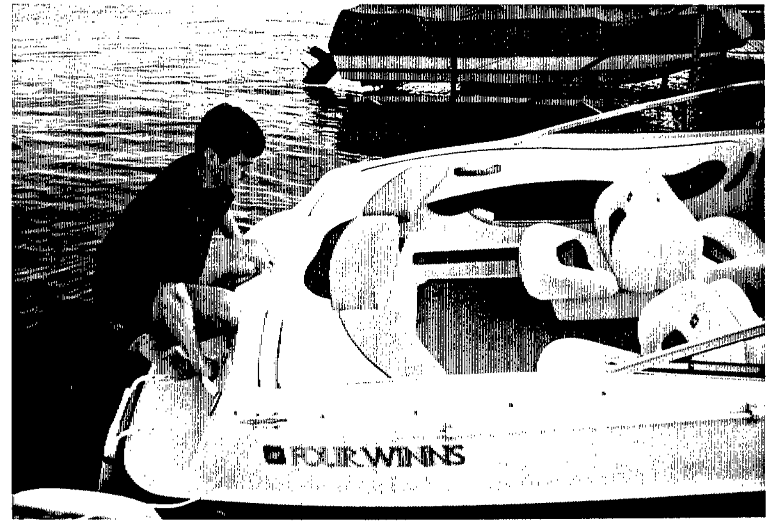

Photo E-10 Task E. Transitioning
Cockpit to Sundeck to Swim Platform Step 11

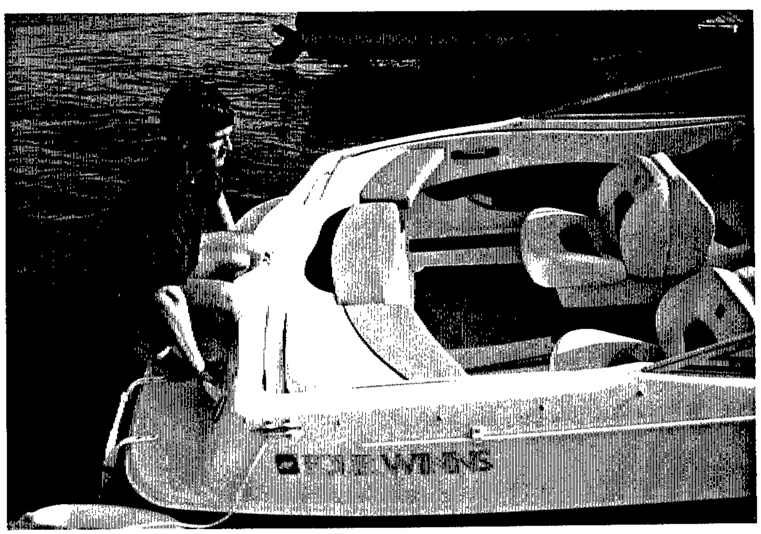

Photo E-11 Task E. Transitioning
Swim Platform to Sundeck to Cockpit Step 1

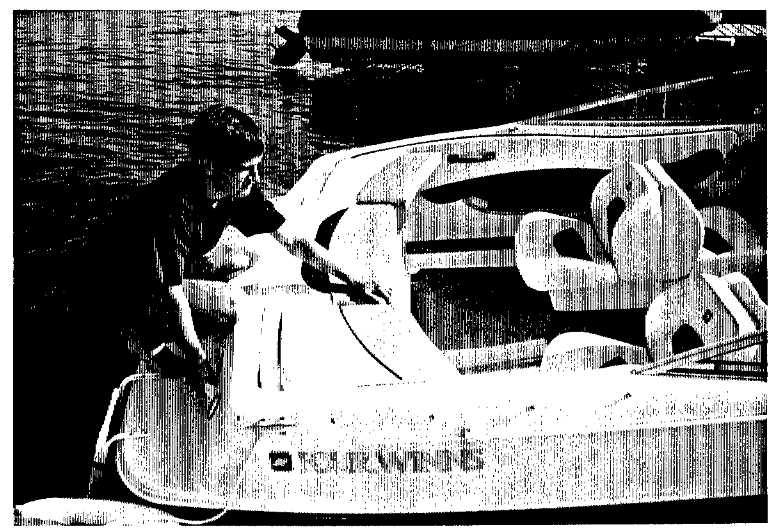

Photo E-12 Task E. Transitioning
Swim Platform to Sundeck to Cockpit Step 2

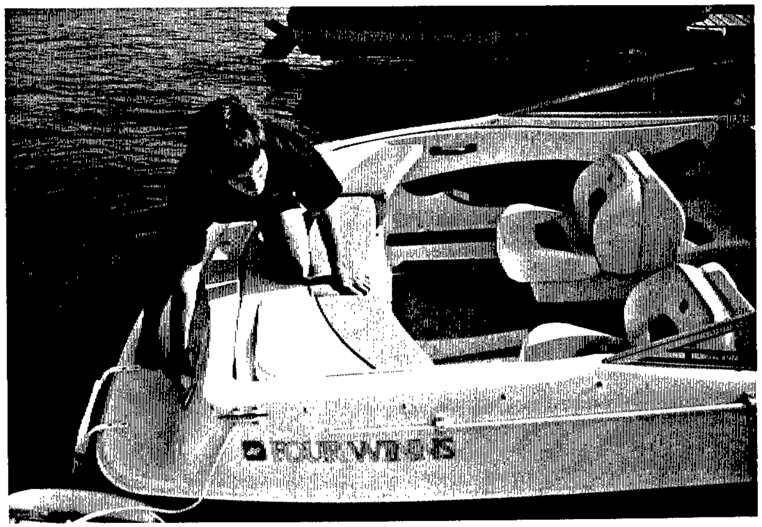

Photo E-13 Task E. Transitioning
Swim Platfrom to Sundeck to Cockpit Step 3

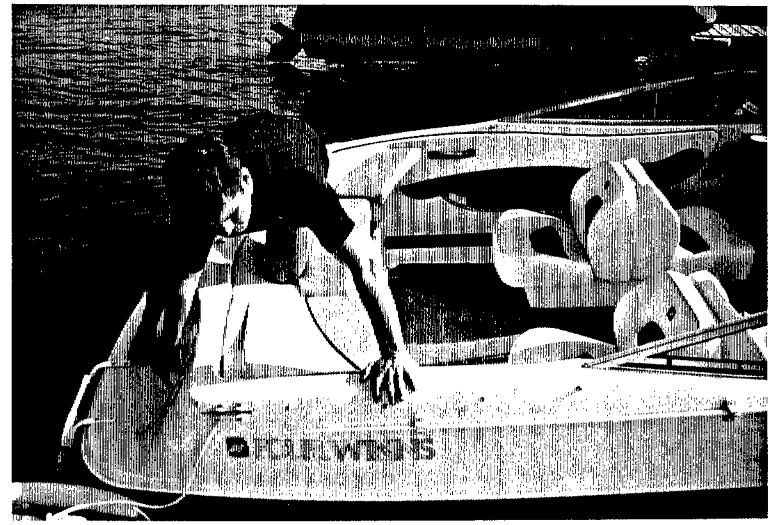

Photo E-14 Task E. Transitioning
Swim Platform to Sundeck to Cockpit Step 4

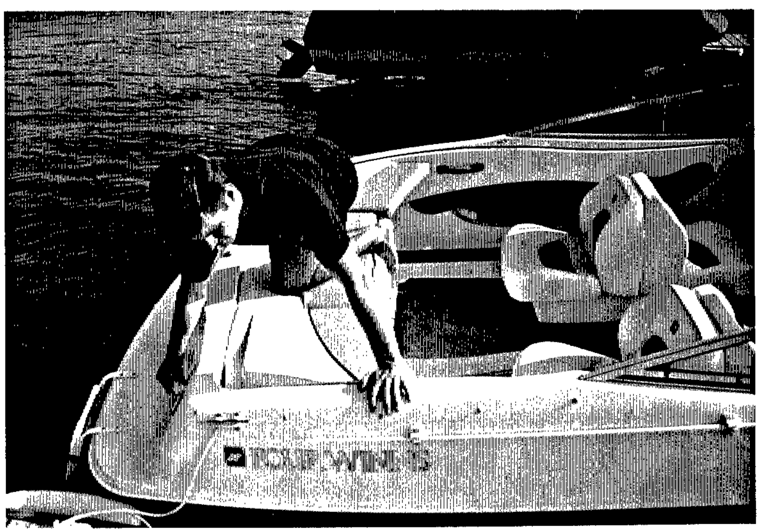

Photo E-15 Task E. Transitioning
Swim Platform to Sundeck to Cockpit Step 5

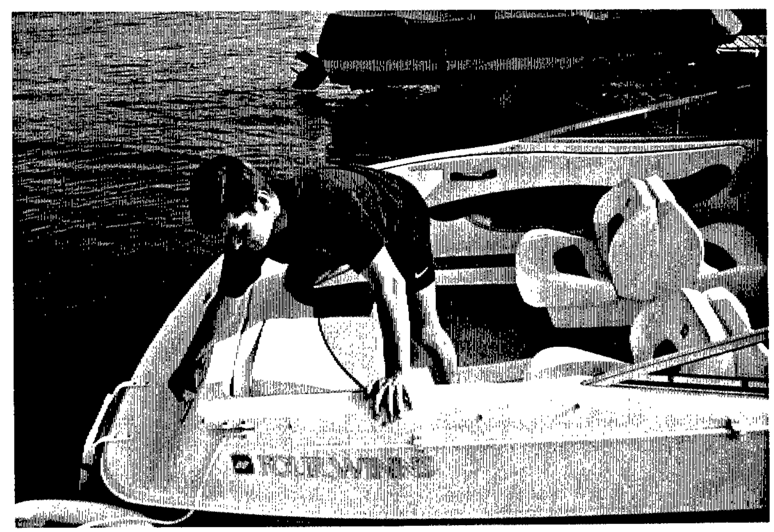

Photo E-16 Task E. Transitioning
Swim Platform to Sundeck to Cockpit Step 6

Photo E-17 Task E. Transitioning
Swim Platfrom to Sundeck to Cockpit Step 7

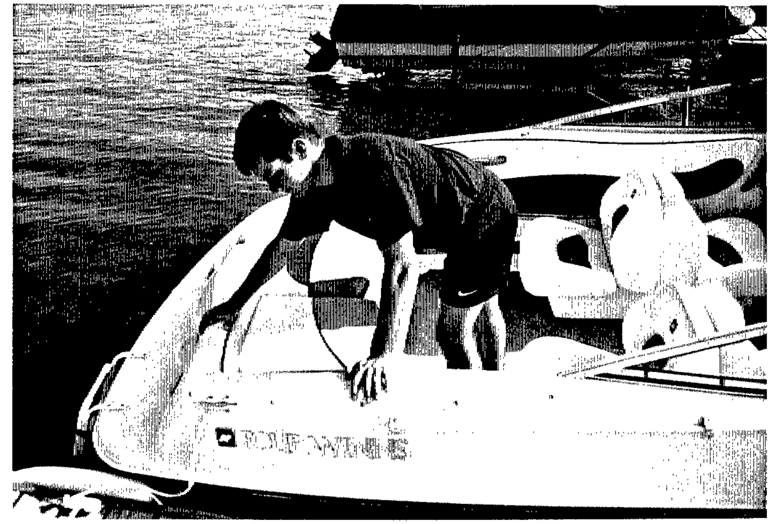

Photo E-18 Task E. Transitioning
Swim Platform to Sundeck to Cockpit Step @

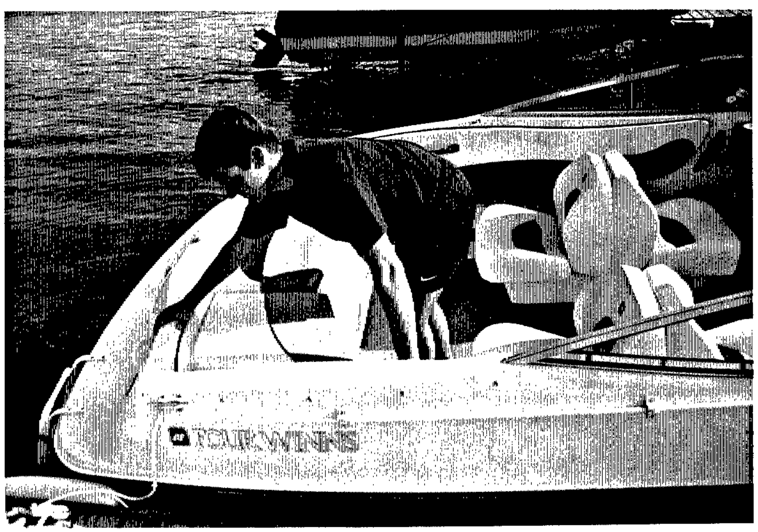

Photo E-19 Task E. Transitioning
Swim Platform to Sundeck to Cockpit Step 9

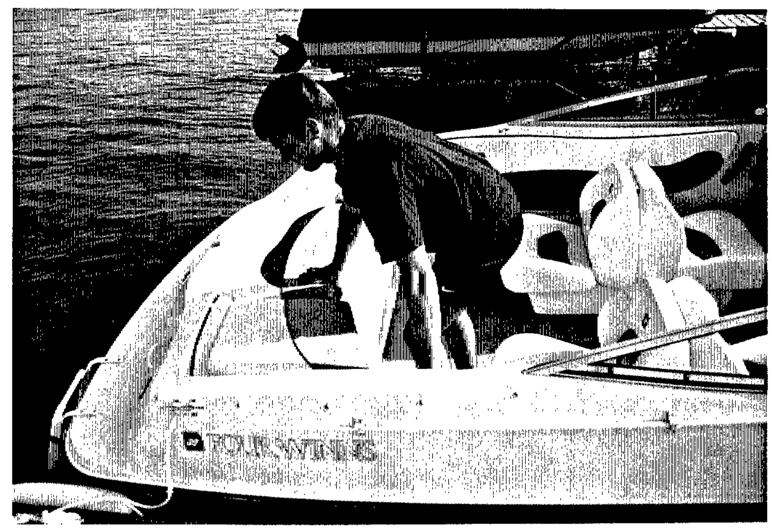

Photo E-20 Task E. Transitioning
Swim Platform to Sundeck to Cockpit Step 10

E-20

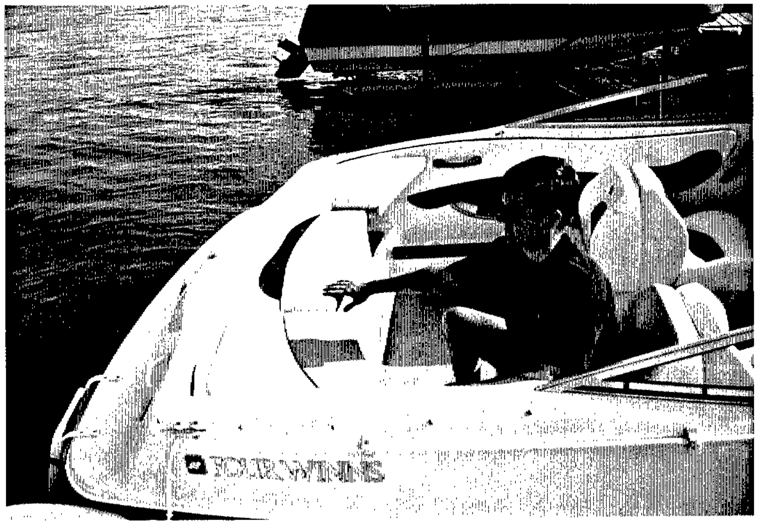

Photo E-21 Task E. Transitioning
Swim Platfrom to Sundeck to Cockpit Step 11

E-21

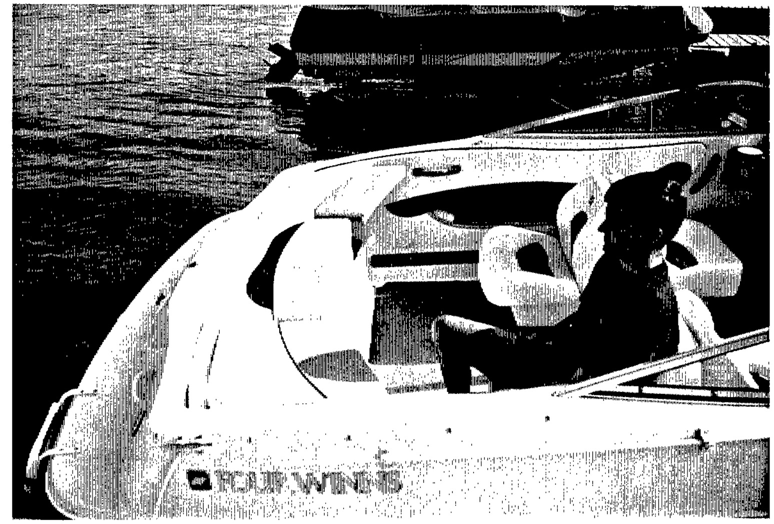

Photo E-22 Task E. Transitioning
Swim Platform to Sundeck to Cockpit Step 12

E-22

Photo E-23 Task F. Emergence/Transitioning
From Water onto Swim Platform Step 1

E-23

Photo E-24 Task F. Emergence/Transitioning
From Water onto Swim Platform Step 2

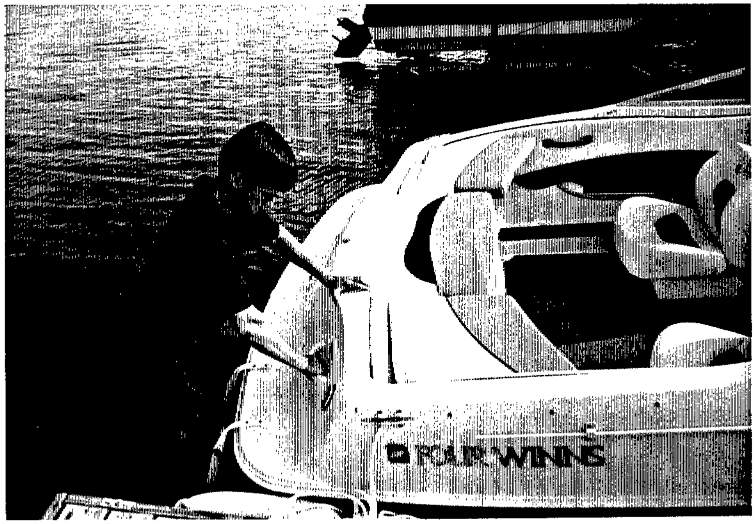

Photo E-25 Task F. Emergence/Transitioning
From Water onto Swim Platform Step 3

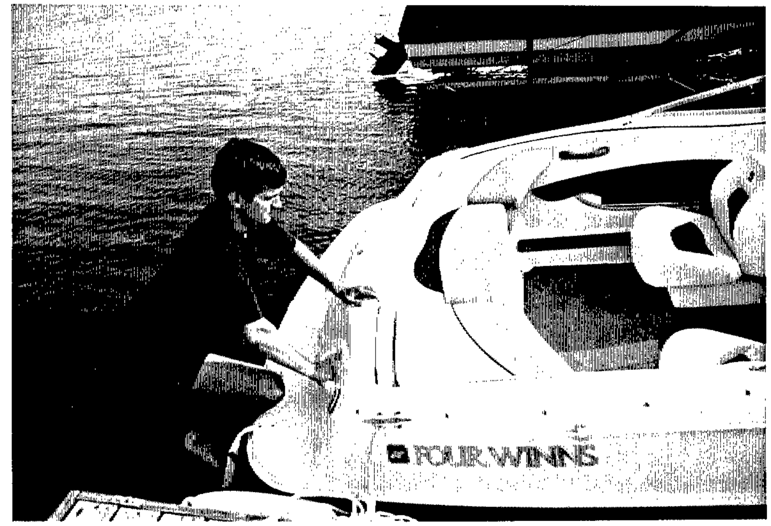

Photo E-26 Task F. Emergence/Transitioning
From Water onto Swim Platform Step 4

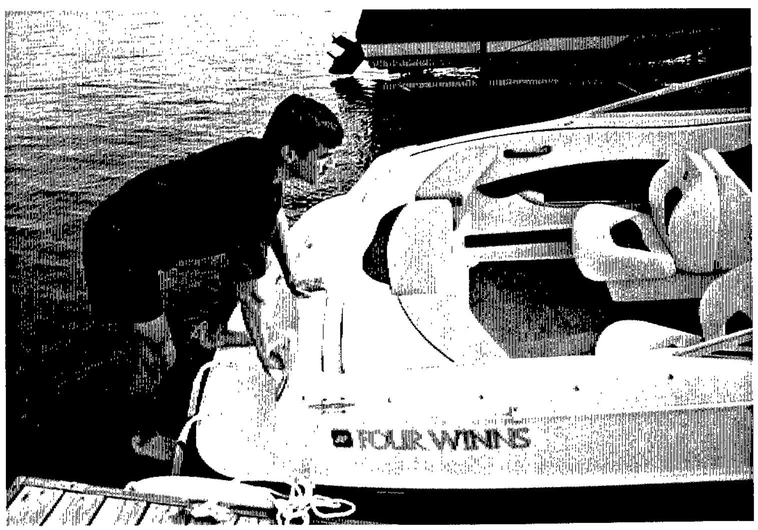

Photo E-27 Task F. Emergence/Transitioning
From Water onto Swim Platform Step 5

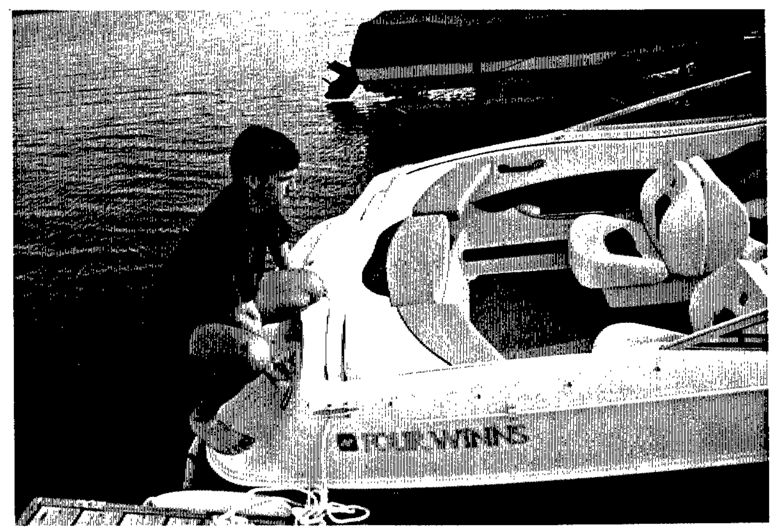

Photo E-28 Task F. Emergence/Transitioning
From Water onto Swim Platform Step 6

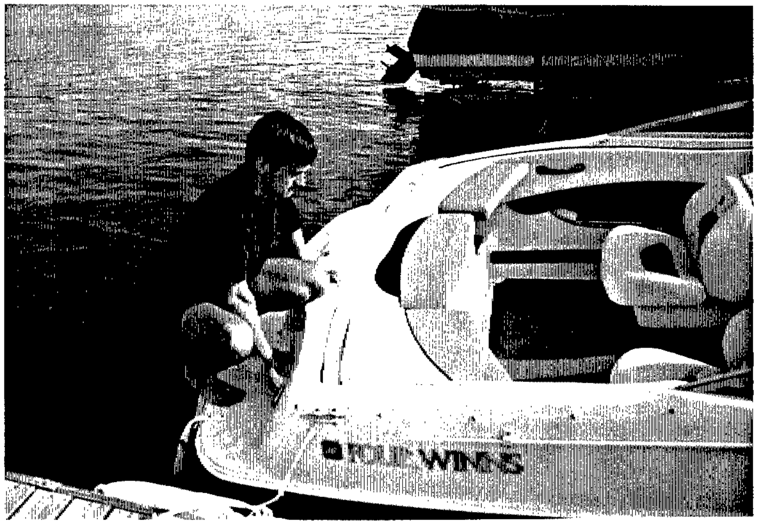

Photo E-29 Task F. Emergence/Transitioning
From Water onto Swim Platform Step 7

Photo E-30 Task F. Emergence/Transitioning
From Water onto Swim Platform Step 8

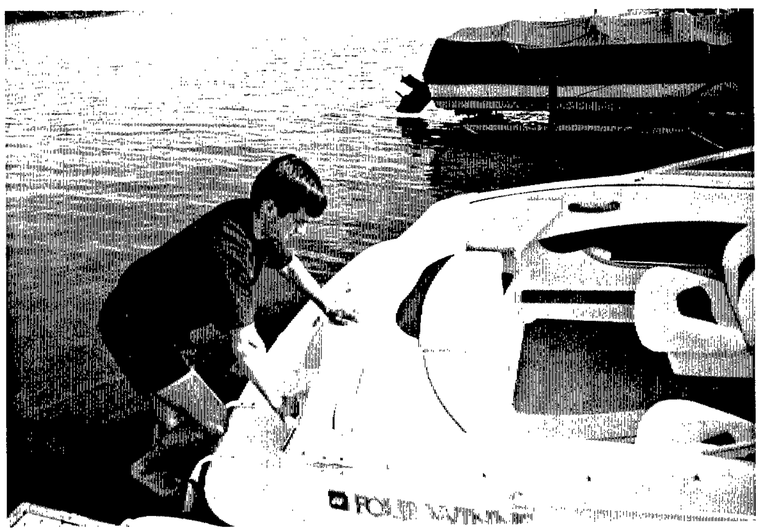

Photo E-31 Task F. Emergence/Transitioning
From Water onto Swim Platform Step 9

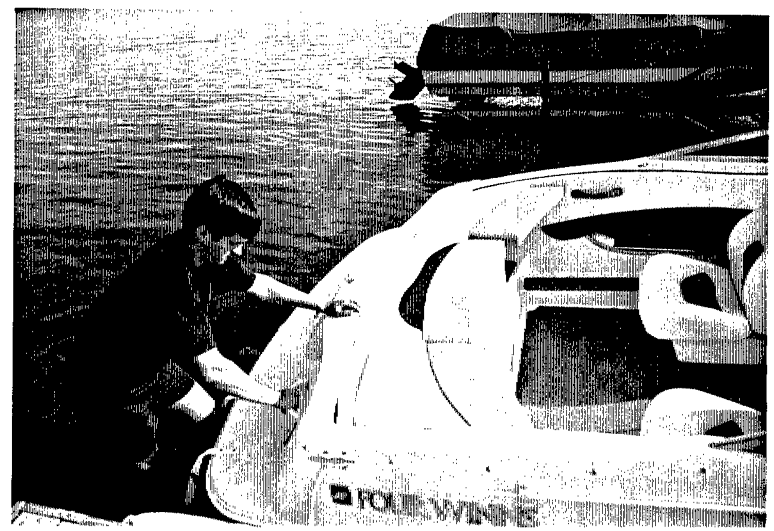

Photo E-31a Task F. Transitioning
From Swim Platform into Water Step 1

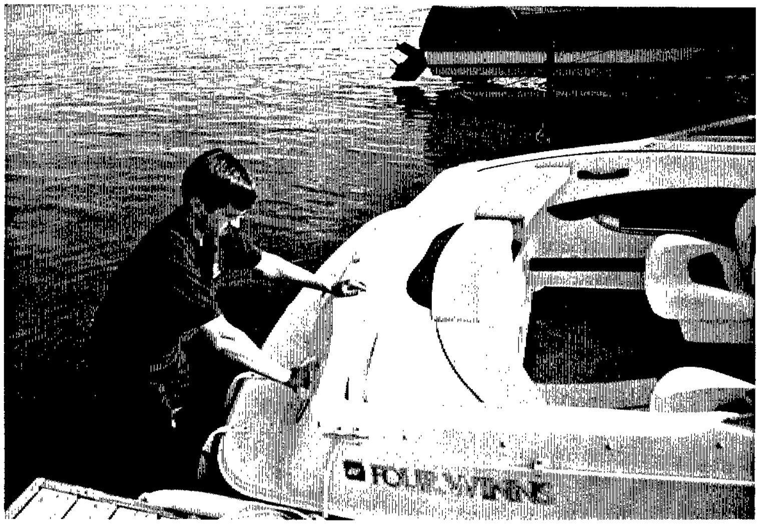

Photo E-32 Task F. Transitioning
From Swim Platform into Water Step 2

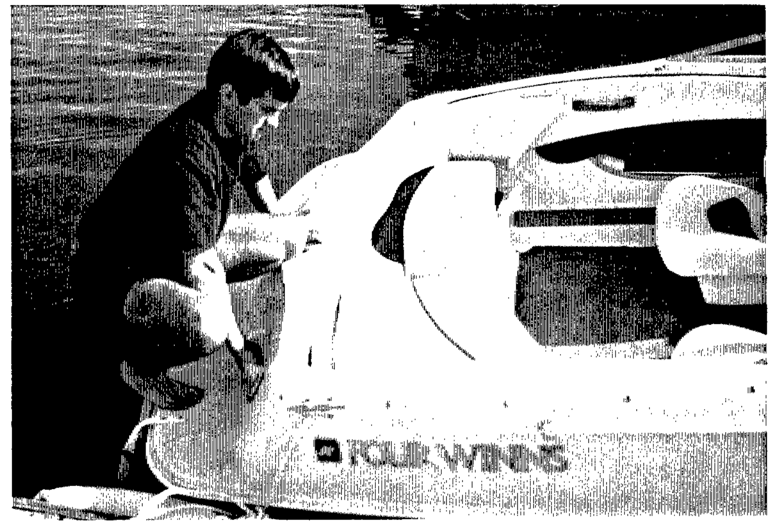

Photo F-1 Task F. Transitioning
From Swim Platform into Water Step 3

Photo F-2 Task F. Transitioning
From Swim Platform into Water Step 4

Photo F-3 Task F. Transitioning
From Swim Platform into Water Step 5

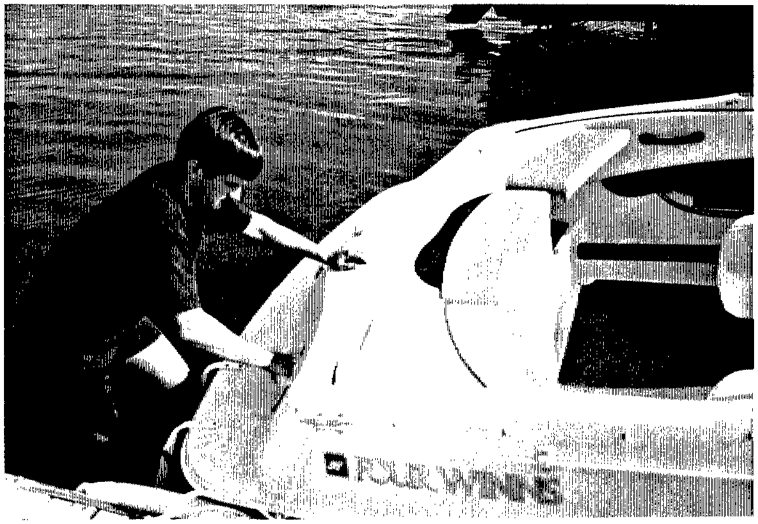

Photo F-4 Task F. Transitioning
From Swim Platform into Water Step 6

Photo F-5 Task F. Transitioning
From Swim Platform into Water Step 7

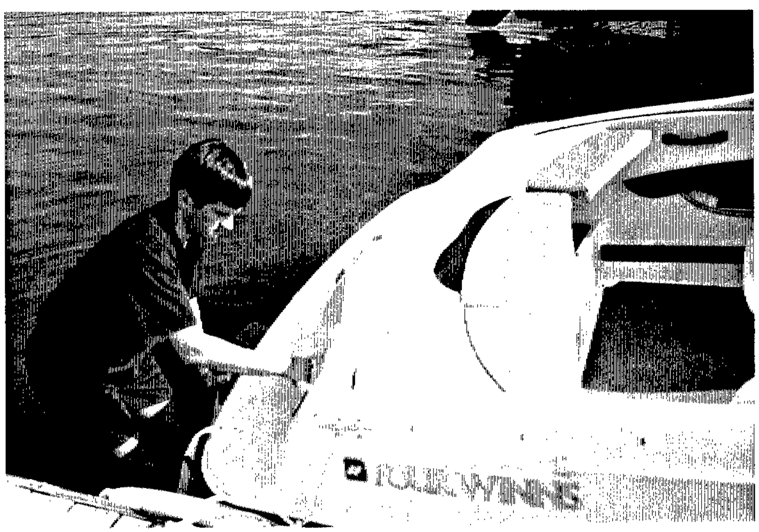

Photo F-6 Task F. Transitioning
From Swim Platform into Water Step 8

Photo F-7 Task F. Transitioning
From Swim Platform into Water Step 9

Photo F-8 Task M. Maneuvering About Swim Platform Step 1

Photo F-9 Task M. Maneuvering About Swim Platform Step 2

Photo F-10 Task M. Maneuvering About Swim Platform Step 3

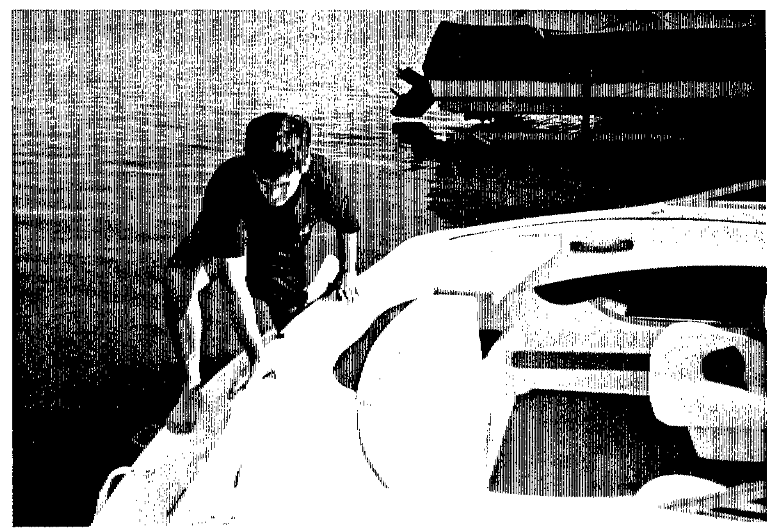

Photo F-11 Task M. Maneuvering About Swim Platform Step 4

Photo F-12 Task M. Maneuvering About Swim Platform Step 5

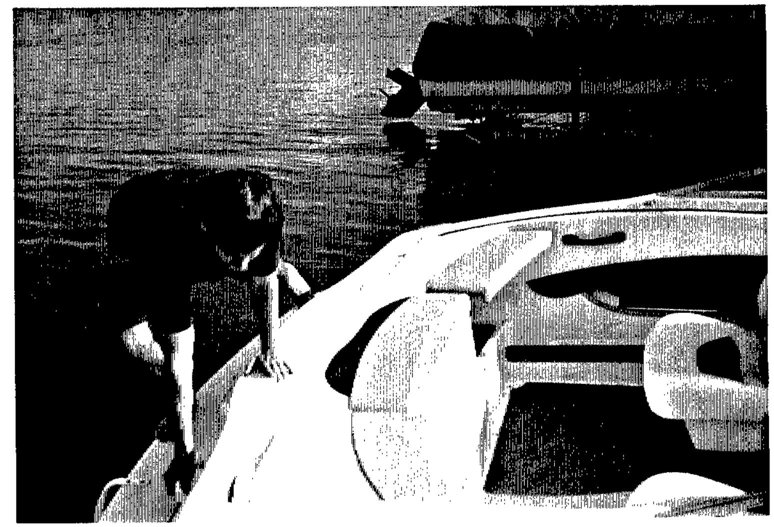

Photo F-13 Task M. Maneuvering About Swim Platform Step 6

Photo F-14 Task M. Maneuvering About Swim Platform Step 7

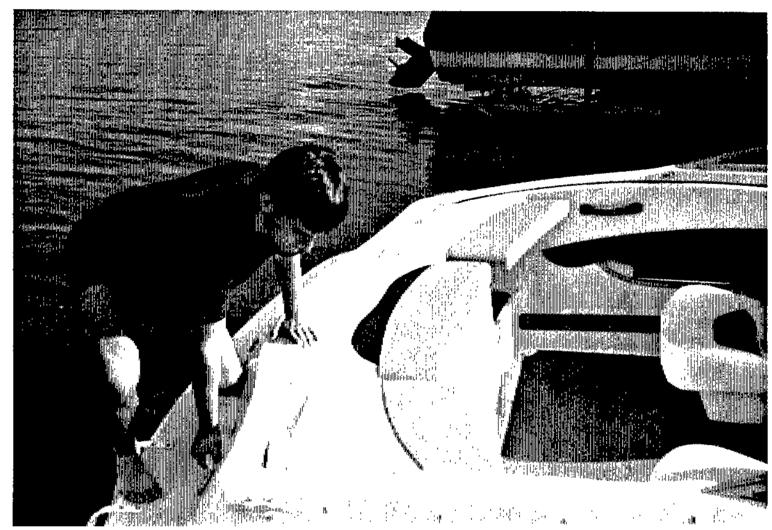

Photo F-15 Task M. Maneuvering About Swim Platform Step 8

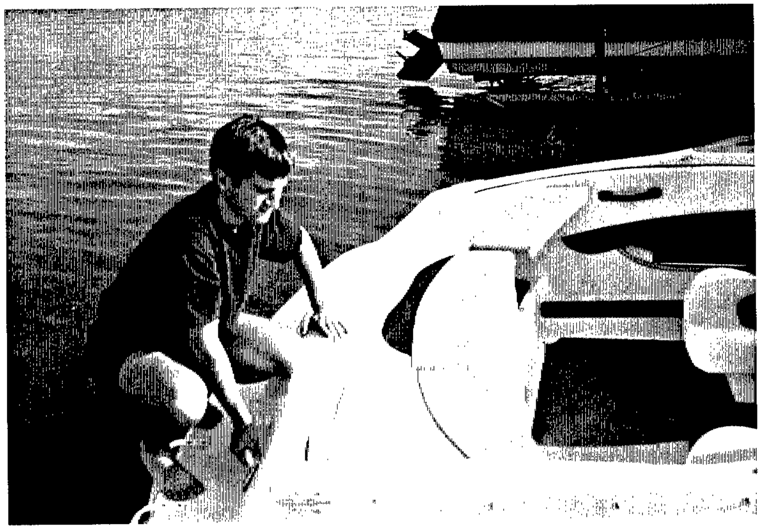

Photo F-16 Task M. Maneuvering
About Swim Platform Step 9

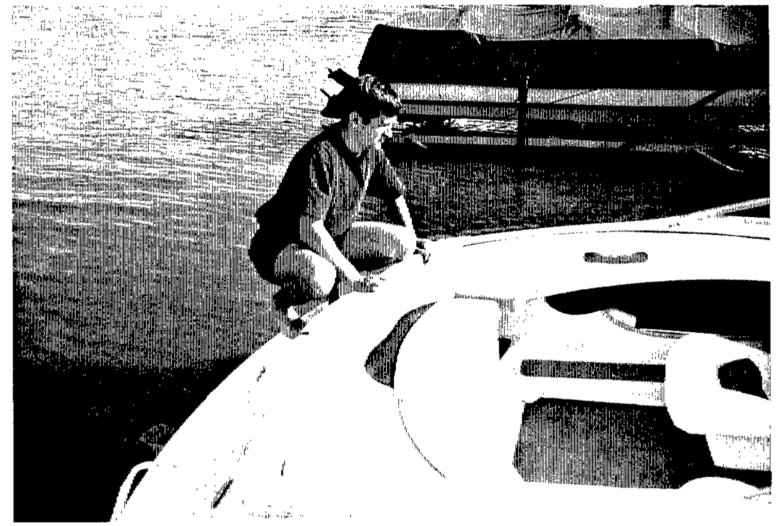

Photo F-17 Task C. Maneuvering
Swim Platform to Sundeck to Cockpit Step 1

Photo F-18 Task C. Maneuvering
Swim Platform to Sundeck to Cockpit Step 2

Photo F-19 Task C. Maneuvering
Swim Platform to Sundeck to Cockpit Step 3

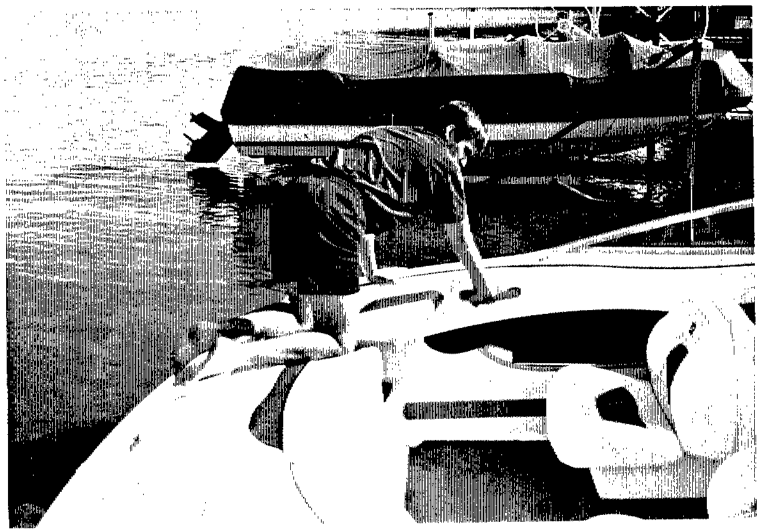

Photo F-20 Task C. Maneuvering
Swim Platform to Sundeck to Cockpit Step 4

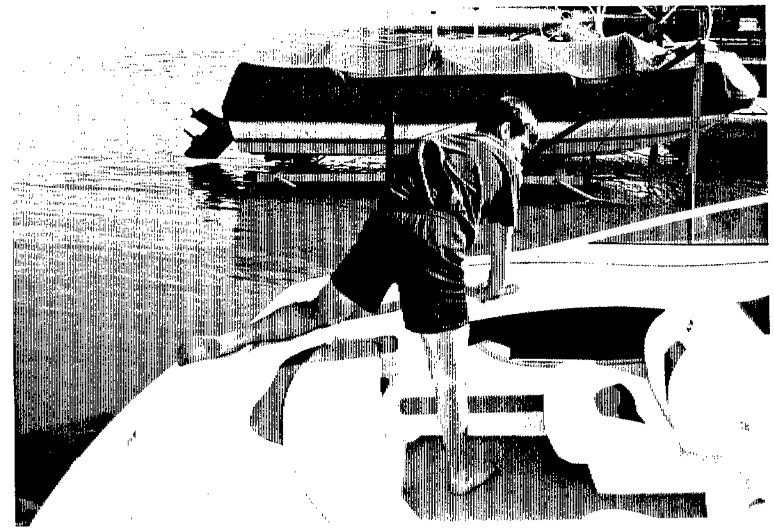

Photo F-21 Task C. Maneuvering
Swim Platform to Sundeck to Cockpit Step 5

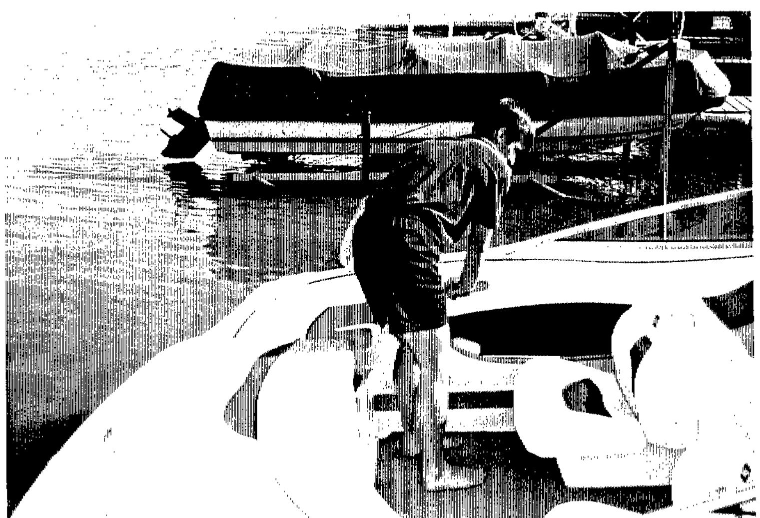

Photo F-22 Task C. Maneuvering
Swim Platform to Sundeck to Cockpit Step 6

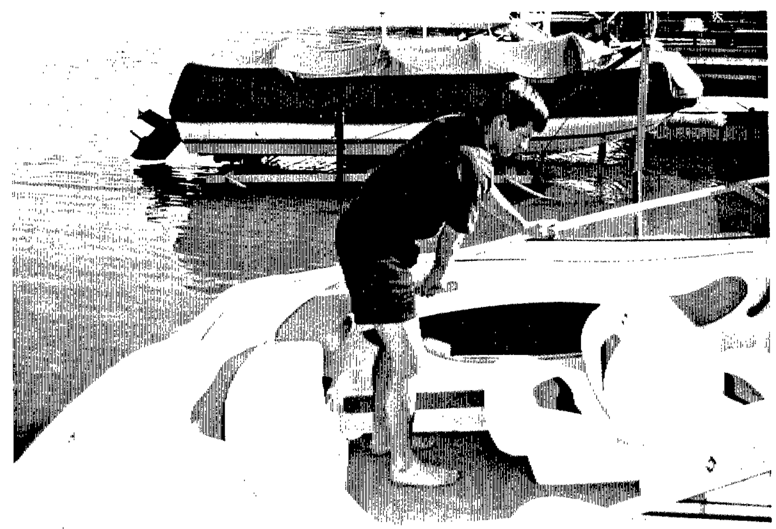

Photo F-23 Task C. Maneuvering
Swim Platform to Sundeck to Cockpit Step 7

Photo F-24 Task C. Maneuvering
Swim Platform to Sundeck to Cockpit Step 8

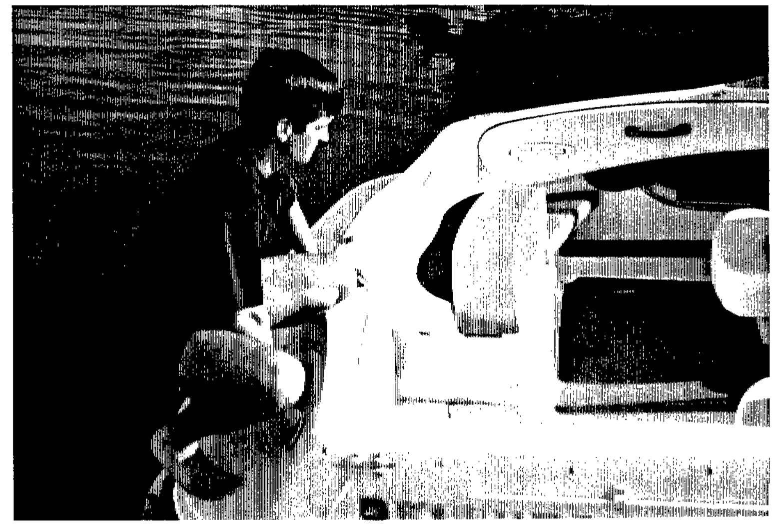

Photo F-24a Task C. Maneuvering
Swim Platform to Cockpit Step 1

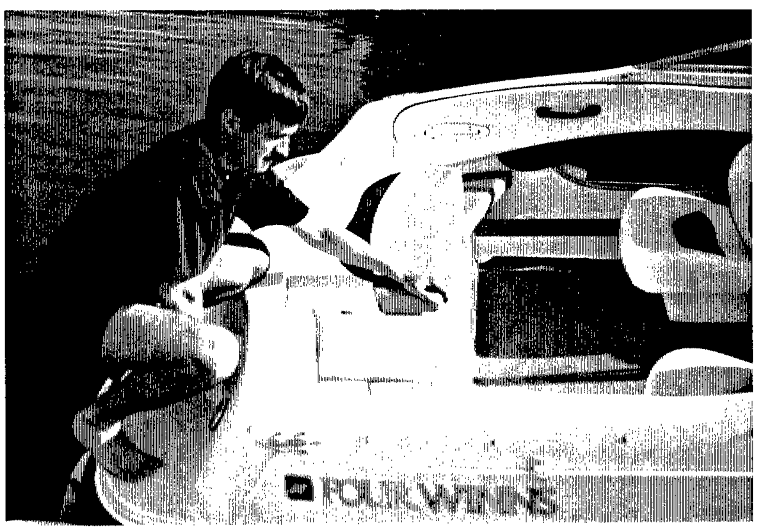

Photo F-25 Task C. Maneuvering
Swim Platform to Cockpit Step 2

Photo F-26 Task C. Maneuvering
Swim Platform to Cockpit Step 3

Photo F-27 Task C. Maneuvering
Swim Platform to Cockpit Step 4

Photo F-28 Task C. Maneuvering
Swim Platform to Cockpit Step 5

Photo F-29 Task C. Maneuvering
Swim Platform to Cockpit Step 6

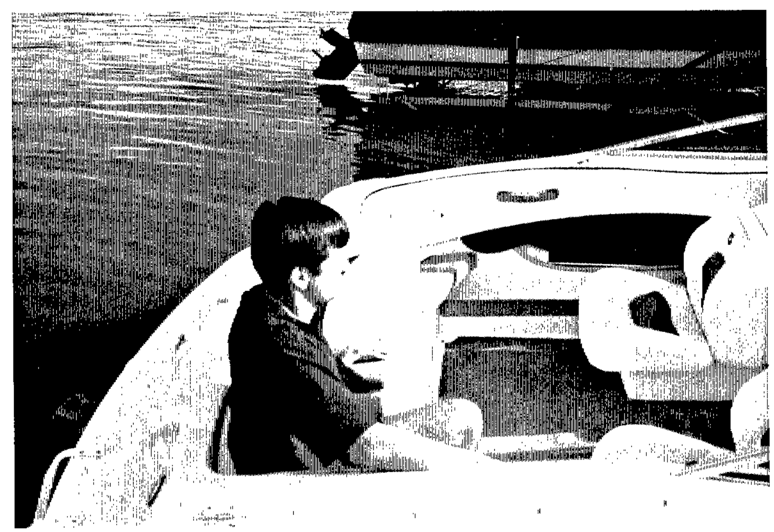

Photo F-30 Task C. Maneuvering
Swim Platform to Cockpit Step 7

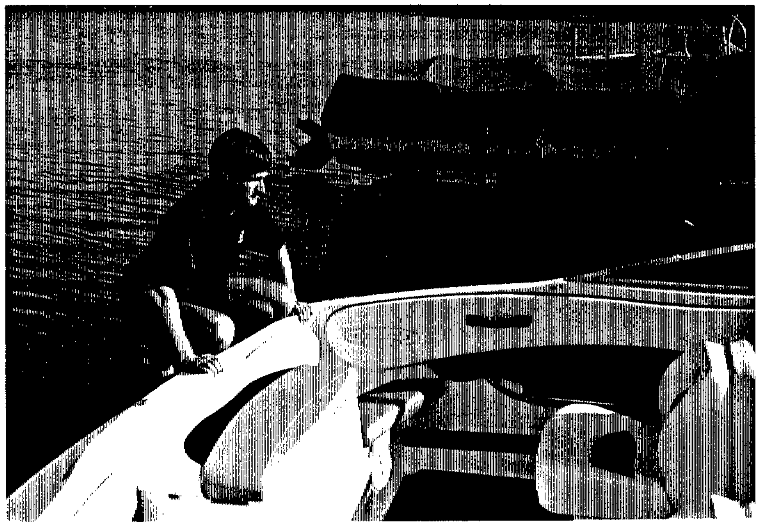

Photo G-1 Task C. Maneuvering
Swim Platform to Cockpit (Trial 2) Step 1

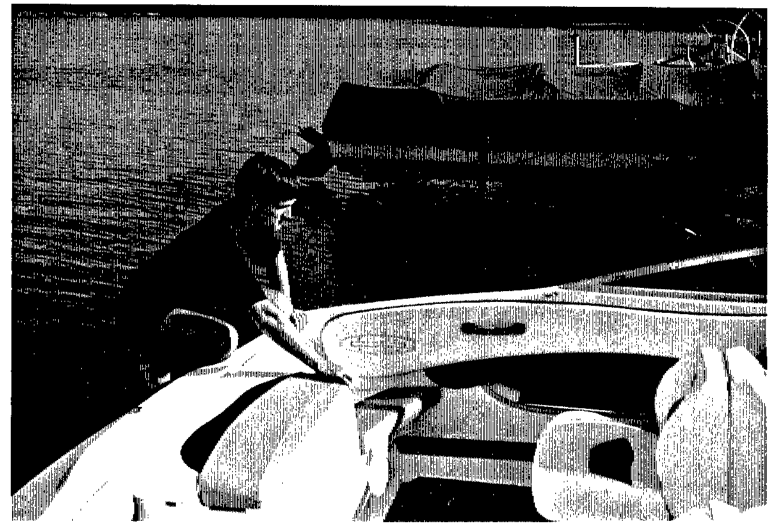

Photo G-2 Task C. Maneuvering
Swim Platform to Cockpit (Trial 2) Step 2

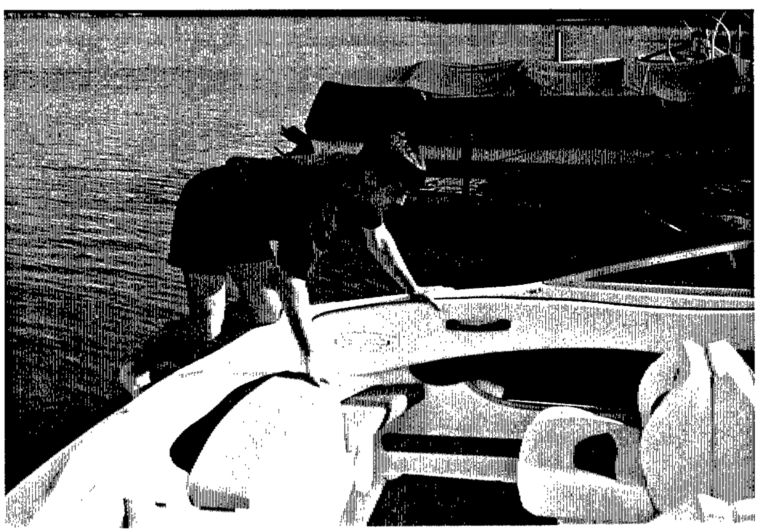

Photo G-3 Task C. Maneuvering
Swim Platform to Cockpit (Trial 2) Step 3

Photo G-4 Task C. Maneuvering
Swim Platform to Cockpit (Trial 2) Step 4

Photo G-5 Task C. Maneuvering
Swim Platform to Cockpit (Trial 2) Step 5

Photo G-6 Task C. Maneuvering
Swim Platform to Cockpit (Trial 2) Step 6

Photo G-7 Task C. Maneuvering
Swim Platform to Cockpit (Trial 2) Step 7

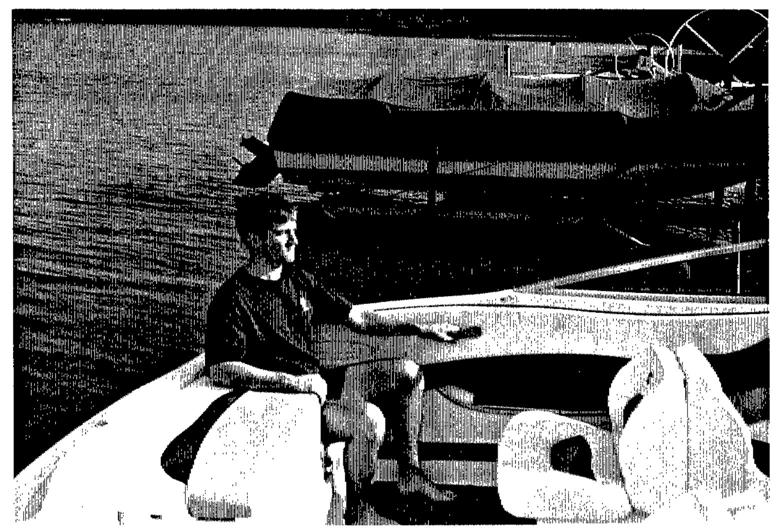

Photo G-9 Task C. Maneuvering
Swim Platform to Cockpit (Trial 2) Step 8

Appendix C

Index to Handhold Use (Appendix B) Photographs

Roll	Photo	Task	Task Location	Sequence
A	0	K. Ingress/Egress	Bow	Step 1
A	1	K. Ingress/Egress	Bow	Step 2
A	2	K. Ingress/Egress	Bow	Step 3
A	3	K. Ingress/Egress	Bow	Step 4
A	4	K. Ingress/Egress	Bow	Step 5
A	5	K. Ingress/Egress	Bow	Step 6
A	6	K. Ingress/Egress	Bow	Step 7
A	7	K. Ingress/Egress	Bow	Step 8
A	8	K. Ingress/Egress	Bow (Trial 2)	Step 1
A	9	K. Ingress/Egress	Bow (Trial 2)	Step 2
A	10	K. Ingress/Egress	Bow (Trial 2)	Step 3
A	11	K. Ingress/Egress	Bow (Trial 2)	Step 4
A	12	K. Ingress/Egress	Bow (Trial 2)	Step 5
A	13	K. Ingress/Egress	Bow (Trial 2)	Step 6
A	14	K. Ingress/Egress	Bow (Trial 2)	Step 7
A	15	K. Ingress/Egress	Amidships	Step 1
A	16	K. Ingress/Egress	Amidships	Step 2
A	17	K. Ingress/Egress	Amidships	Step 3
A	18	K. Ingress/Egress	Amidships	Step 4
A	19	K. Ingress/Egress	Amidships	Step 5
A	20	K. Ingress/Egress	Amidships	Step 6
A	21	K. Ingress/Egress	Stern	Step 1
A	22	K. Ingress/Egress	Stern	Step 2
A	23	K. Ingress/Egress	Stern	Step 3
A	24	K. Ingress/Egress	Stern	Step 4
A	25	K. Ingress/Egress	Stern	Step 5
A	26	K. Ingress/Egress	Stern	Step 6
A	27	K. Ingress/Egress	Stern	Step 7
A	28	L. Stabilization	Stern Seat	Step 1
A	29	L. Stabilization	Aft Facing Back-to-Back Seat	Step 1
A	30	L. Stabilization	Seat Opposite Helm	Step 1
A	31	L. Stabilization	Seat Opposite Helm (Trial 2)	Step 1
A	32	I. Stabilization	Bow Seat	Step 1
A	33	I. Stabilization	Bow Seat (Trial 2)	Step 1
A	34	A. Maneuvering	Cockpit to Bow Seating Area	Step 1
A	35	A. Maneuvering	Cockpit to Bow Seating Area	Step 2
A	36	A. Maneuvering	Cockpit to Bow Seating Area	Step 3
B	0	A. Maneuvering	Cockpit to Bow Seating Area	Step 4
B	1	A. Maneuvering	Cockpit to Bow Seating Area	Step 5
B	2	A. Maneuvering	Cockpit to Bow Seating Area	Step 6
B	3	A. Maneuvering	Cockpit to Bow Seating Area	Step 7
B	4	A. Maneuvering	Cockpit to Bow Seating Area	Step 8
B	5	A. Maneuvering	Cockpit to Bow Seating Area	Step 9
B	6	A. Maneuvering	Cockpit to Bow Seating Area	Step 10
B	7	A. Maneuvering	Cockpit to Bow Seating Area	Step 11
B	8	A. Maneuvering	Cockpit to Bow Seating Area	Step 12
B	9	A. Maneuvering	Cockpit to Bow Seating Area	Step 13

B	10	D. Maneuvering about Cockpit	Fore to Aft	Step 1
B	11	D. Maneuvering about Cockpit	Fore to Aft	Step 2
B	12	D. Maneuvering about Cockpit	Fore to Aft	Step 3
B	13	D. Maneuvering about Cockpit	Fore to Aft	Step 4
B	14	D. Maneuvering about Cockpit	Fore to Aft	Step 5
B	15	D. Maneuvering about Cockpit	Fore to Aft	Step 6
B	16	D. Maneuvering about Cockpit	Fore to Aft	Step 7
B	17	D. Maneuvering about Cockpit	Fore to Aft	Step 8
B	20	D. Maneuvering about Cockpit	Fore to Aft	Step 9
B	21	D. Maneuvering about Cockpit	Fore to Aft	Step 10
B	22	D. Maneuvering about Cockpit	Fore to Aft	Step 11
B	23	D. Maneuvering about Cockpit	Fore to Aft	Step 12
B	24	D. Maneuvering about Cockpit	Fore to Aft	Step 13
B	25	E. Maneuvering about Cockpit	Port to Starboard	Step 1
B	26	E. Maneuvering about Cockpit	Port to Starboard	Step 2
B	27	E. Maneuvering about Cockpit	Port to Starboard	Step 3
B	28	E. Maneuvering about Cockpit	Port to Starboard	Step 4
B	29	E. Maneuvering about Cockpit	Port to Starboard	Step 5
B	30	E. Maneuvering about Cockpit	Port to Starboard	Step 6
B	31	E. Maneuvering about Cockpit	Port to Starboard	Step 7
B	32	E. Maneuvering about Cockpit	Port to Starboard	Step 8
B	33	E. Maneuvering about Cockpit	Port to Starboard	Step 9
C	0	E. Maneuvering about Cockpit	Starboard to Port	Step 1
C	1	E. Maneuvering about Cockpit	Starboard to Port	Step 2
C	2	E. Maneuvering about Cockpit	Starboard to Port	Step 3
C	3	E. Maneuvering about Cockpit	Starboard to Port	Step 4
C	4	E. Maneuvering about Cockpit	Starboard to Port	Step 5
C	5	E. Maneuvering about Cockpit	Starboard to Port	Step 6
C	6	E. Maneuvering about Cockpit	Starboard to Port	Step 7
C	7	E. Maneuvering about Cockpit	Starboard to Port	Step 8
C	8	E. Maneuvering about Cockpit	Starboard to Port	Step 9
C	9	E. Maneuvering about Cockpit	Starboard to Port	Step 10
C	10	E. Maneuvering about Cockpit	Port to Starboard	Step 1
C	11	E. Maneuvering about Cockpit	Port to Starboard	Step 2
C	12	E. Maneuvering about Cockpit	Port to Starboard	Step 3
C	13	E. Maneuvering about Cockpit	Port to Starboard	Step 4
C	14	E. Maneuvering about Cockpit	Port to Starboard	Step 5
C	15	E. Maneuvering about Cockpit	Port to Starboard	Step 6
C	16	E. Maneuvering about Cockpit	Port to Starboard	Step 7
C	17	E. Maneuvering about Cockpit	Port to Starboard	Step 8
C	18	E. Maneuvering about Cockpit	Port to Starboard	Step 9
C	19	E. Maneuvering about Cockpit	Port to Starboard	Step 10
C	20	E. Maneuvering about Cockpit	Port to Starboard	Step 11
C	21	A. Maneuvering	Bow Seating Area to Cockpit	Step 1
C	22	A. Maneuvering	Bow Seating Area to Cockpit	Step 2
C	23	A. Maneuvering	Bow Seating Area to Cockpit	Step 3
C	24	A. Maneuvering	Bow Seating Area to Cockpit	Step 4
C	25	A. Maneuvering	Bow Seating Area to Cockpit	Step 5

C	26	A. Maneuvering	Bow Seating Area to Cockpit	Step 6
C	27	A. Maneuvering	Bow Seating Area to Cockpit	Step 7
C	28	A. Maneuvering	Bow Seating Area to Cockpit	Step 8
C	29	A. Maneuvering	Bow Seating Area to Cockpit	Step 9
C	30	A. Maneuvering	Bow Seating Area to Cockpit	Step 10
C	31	A. Maneuvering	Bow Seating Area to Cockpit	Step 11
C	32	A. Maneuvering	Bow Seating Area to Cockpit	Step 12
C	33	A. Maneuvering	Bow Seating Area to Cockpit (Trial 2)	Step 1
C	34	A. Maneuvering	Bow Seating Area to Cockpit (Trial 2)	Step 2
C	35	A. Maneuvering	Bow Seating Area to Cockpit (Trial 2)	Step 3
D	0	A. Maneuvering	Bow Seating Area to Cockpit (Trial 2)	Step 4
D	1	A. Maneuvering	Bow Seating Area to Cockpit (Trial 2)	Step 5
D	2	A. Maneuvering	Bow Seating Area to Cockpit (Trial 2)	Step 6
D	3	A. Maneuvering	Bow Seating Area to Cockpit (Trial 2)	Step 7
D	4	A. Maneuvering	Bow Seating Area to Cockpit (Trial 2)	Step 8
D	5	A. Maneuvering	Bow Seating Area to Cockpit (Trial 2)	Step 9
D	6	A. Maneuvering	Bow Seating Area to Cockpit (Trial 2)	Step 10
D	7	H. Maneuvering About Bow	Port to Starboard	Step 1
D	8	H. Maneuvering About Bow	Port to Starboard	Step 2
D	9	H. Maneuvering About Bow	Port to Starboard	Step 3
D	10	H. Maneuvering About Bow	Port to Starboard	Step 4
D	11	H. Maneuvering About Bow	Port to Starboard	Step 5
D	12	H. Maneuvering About Bow	Port to Starboard	Step 6
D	13	H. Maneuvering About Bow	Port to Starboard	Step 7
D	14	H. Maneuvering About Bow	Port to Starboard	Step 8
D	15	H. Maneuvering About Bow	Port to Starboard	Step 9
D	16	E. Maneuvering about Cockpit	Port to Starboard	Step 1
D	17	E. Maneuvering about Cockpit	Port to Starboard	Step 2
D	18	E. Maneuvering about Cockpit	Port to Starboard	Step 3
D	19	E. Maneuvering about Cockpit	Port to Starboard	Step 4
D	20	E. Maneuvering about Cockpit	Port to Starboard	Step 5
D	21	E. Maneuvering about Cockpit	Port to Starboard	Step 6
D	22	E. Maneuvering about Cockpit	Port to Starboard	Step 7
D	23	E. Maneuvering about Cockpit	Port to Starboard	Step 8
D	24	E. Maneuvering about Cockpit	Port to Starboard	Step 9
D	25	E. Maneuvering about Cockpit	Port to Starboard	Step 10
D	26	C. Transitioning	Cockpit to Sun Deck to Swim Platform	Step 1
E	1	C. Transitioning	Cockpit to Sun Deck to Swim Platform	Step 2
E	2	C. Transitioning	Cockpit to Sun Deck to Swim Platform	Step 3
E	3	C. Transitioning	Cockpit to Sun Deck to Swim Platform	Step 4
E	4	C. Transitioning	Cockpit to Sun Deck to Swim Platform	Step 5
E	5	C. Transitioning	Cockpit to Sun Deck to Swim Platform	Step 6
E	6	C. Transitioning	Cockpit to Sun Deck to Swim Platform	Step 7
E	7	C. Transitioning	Cockpit to Sun Deck to Swim Platform	Step 8
E	8	C. Transitioning	Cockpit to Sun Deck to Swim Platform	Step 9
E	9	C. Transitioning	Cockpit to Sun Deck to Swim Platform	Step 10
E	10	C. Transitioning	Cockpit to Sun Deck to Swim Platform	Step 11
E	11	C. Transitioning	Swim Platform to Sun Deck to Cockpit	Step 1

E	12	C. Transitioning	Swim Platform to Sun Deck to Cockpit	Step 2
E	13	C. Transitioning	Swim Platform to Sun Deck to Cockpit	Step 3
E	14	C. Transitioning	Swim Platform to Sun Deck to Cockpit	Step 4
E	15	C. Transitioning	Swim Platform to Sun Deck to Cockpit	Step 5
E	16	C. Transitioning	Swim Platform to Sun Deck to Cockpit	Step 6
E	17	C. Transitioning	Swim Platform to Sun Deck to Cockpit	Step 7
E	18	C. Transitioning	Swim Platform to Sun Deck to Cockpit	Step 8
E	19	C. Transitioning	Swim Platform to Sun Deck to Cockpit	Step 9
E	20	C. Transitioning	Swim Platform to Sun Deck to Cockpit	Step 10
E	21	C. Transitioning	Swim Platform to Sun Deck to Cockpit	Step 11
E	22	C. Transitioning	Swim Platform to Sun Deck to Cockpit	Step 12
E	23	F. Emergence/Transitioning	From Water onto Swim Platform	Step 1
E	24	F. Emergence/Transitioning	From Water onto Swim Platform	Step 2
E	25	F. Emergence/Transitioning	From Water onto Swim Platform	Step 3
E	26	F. Emergence/Transitioning	From Water onto Swim Platform	Step 4
E	27	F. Emergence/Transitioning	From Water onto Swim Platform	Step 5
E	28	F. Emergence/Transitioning	From Water onto Swim Platform	Step 6
E	29	F. Emergence/Transitioning	From Water onto Swim Platform	Step 7
E	30	F. Emergence/Transitioning	From Water onto Swim Platform	Step 8
E	31	F. Emergence/Transitioning	From Water onto Swim Platform	Step 9
E	31a	F. Transitioning	From Swim Platform into Water	Step 1
E	32	F. Transitioning	From Swim Platform into Water	Step 2
F	1	F. Transitioning	From Swim Platform into Water	Step 3
F	2	F. Transitioning	From Swim Platform into Water	Step 4
F	3	F. Transitioning	From Swim Platform into Water	Step 5
F	4	F. Transitioning	From Swim Platform into Water	Step 6
F	5	F. Transitioning	From Swim Platform into Water	Step 7
F	6	F. Transitioning	From Swim Platform into Water	Step 8
F	7	F. Transitioning	From Swim Platform into Water	Step 9
F	8	M. Maneuvering	About Swim Platform	Step 1
F	9	M. Maneuvering	About Swim Platform	Step 2
F	10	M. Maneuvering	About Swim Platform	Step 3
F	11	M. Maneuvering	About Swim Platform	Step 4
F	12	M. Maneuvering	About Swim Platform	Step 5
F	13	M. Maneuvering	About Swim Platform	Step 6
F	14	M. Maneuvering	About Swim Platform	Step 7
F	15	M. Maneuvering	About Swim Platform	Step 8
F	16	M. Maneuvering	About Swim Platform	Step 9
F	17	C. Maneuvering	Swim Platform to Sun Deck to Cockpit	Step 1
F	18	C. Maneuvering	Swim Platform to Sun Deck to Cockpit	Step 2
F	19	C. Maneuvering	Swim Platform to Sun Deck to Cockpit	Step 3
F	20	C. Maneuvering	Swim Platform to Sun Deck to Cockpit	Step 4
F	21	C. Maneuvering	Swim Platform to Sun Deck to Cockpit	Step 5
F	22	C. Maneuvering	Swim Platform to Sun Deck to Cockpit	Step 6
F	23	C. Maneuvering	Swim Platform to Sun Deck to Cockpit	Step 7
F	24	C. Maneuvering	Swim Platform to Sun Deck to Cockpit	Step 8
F	24a	C. Maneuvering	Swim Platform to Cockpit	Step 1
F	25	C. Maneuvering	Swim Platform to Cockpit	Step 2

F	26	C. Maneuvering	Swim Platform to Cockpit	Step 3
F	27	C. Maneuvering	Swim Platform to Cockpit	Step 4
F	28	C. Maneuvering	Swim Platform to Cockpit	Step 5
F	29	C. Maneuvering	Swim Platform to Cockpit	Step 6
F	30	C. Maneuvering	Swim Platform to Cockpit	Step 7
G	1	C. Maneuvering	Swim Platform to Cockpit (Trial 2)	Step 1
G	2	C. Maneuvering	Swim Platform to Cockpit (Trial 2)	Step 2
G	3	C. Maneuvering	Swim Platform to Cockpit (Trial 2)	Step 3
G	4	C. Maneuvering	Swim Platform to Cockpit (Trial 2)	Step 4
G	5	C. Maneuvering	Swim Platform to Cockpit (Trial 2)	Step 5
G	6	C. Maneuvering	Swim Platform to Cockpit (Trial 2)	Step 6
G	7	C. Maneuvering	Swim Platform to Cockpit (Trial 2)	Step 7
G	9	C. Maneuvering	Swim Platform to Cockpit (Trial 2)	Step 8

BOWRIDER BACKREST HEIGHT VARIABLES

AN EXPERIMENTAL AND SIMULATION STUDY, PART II

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Table of Contents

List of Tables

List of Figures

BOWRIDER BACKREST HEIGHT VARIABLES ·
AN EXPERIMENTAL AND SIMULATION STUDY, PART II

INTRODUCTION

This study was conducted as a follow-up to a computer simulation study conducted by Miller, Grieser, and Clark (1996). The occupant ejection prediction model it used was created to explore backrest height as a factor in containing occupants within a boat during moderately severe maneuvers. Findings from that study suggested that:

1. a six inch backrest is inadequate in that it did not prevent occupant ejection,
2. a nine inch backrest is conditionally adequate, where there are not any downward accelerations great enough to leave the occupant airborne, and
3. a twelve inch backrest appeared adequate even for conditions where an occupant's buttocks occasionally rise up to three inches above and away from the seat bottom.

The purpose of this present study was to increase the accuracy, flexibility, and usefulness of the occupant ejection prediction model. This was done through a number of enhancements (**Table 1**). We also wished to verify the previous human/boat model's results.

One of the most significant enhancements in the new human/boat model is that it is now dynamically driven by actual accelerometer data collected on the water by us in various boats. This was done by us in a previous U.S. Coast Guard study funded through the American Boat & Yacht Council. Previously, the model was driven by a constant lateral acceleration for a specified duration.

Another significant enhancement in the new computer model is its expansion to accommodate three dimensions. While the previous human/boat model operated only in the sagittal (side) plane, the current model includes the frontal plane, also.

Finally, the human model joints were given passive resistances to motion in order to characterize muscle strength effects and allow the human body models to hold their initial postures. This was simulated by using variable torsional springs and dash pots. This substantially increases the fidelity of the simulation model.

Table 1: Significant Occupant Ejection Prediction Model Enhancements

	Previous Human/Boat Model	**New Human/Boat Model**
Dimensions Represented	2: sagittal (side) plane	3: sagittal and frontal planes
How Driven	Constant one axis linear acceleration of a specified duration	Actual on-water boat motion accelerometer data
Muscle Strength Effects/Posture	None	Torsional spring/ dash pot model

METHODOLOGY

Experimental Methodology/Test Procedure/Data Analysis

The data used to drive the computer model was collected in a previous study (Miller, Grieser and Clark, 1996). Therein, a detailed experimental methodology, test procedure, and data analysis was presented. For the reader's convenience, these sections of that report are included herein as **Appendices B**, **C**, and **D**, respectively.

Modeling the Seated Boat Passenger

As with the previous study, the widely used 50th percentile adult male human body model was selected as the simulation boat occupant. The two planes being modeled can be represented as the Segmented Sagittal Plane and Segmented Frontal Plane Models of the Human Body as shown in **Figures 1** and **2**. Not indifferent from other anthropometric and biomechanical representations, they can be seen as having nine masses in the sagittal plane and thirteen masses in the frontal plane; all of which have their respective center of masses, and moments of inertia, and which, taken collectively, represent the total of the human body. The joints are modeled as pin joints with "rope" elements to simulate range of motions within the normal human body limits. The joints are given passive resistances to motion using variable torsional springs and dash pots in order to characterize occupant muscle strength effects and to allow the human body models to "hold" initial postures as muscles would be expected to do in a real person occupants.

The authors chose not to model the seat cushioning because in the bow seat area, it is often relatively thin and therefore likely has little effect on occupant kinematics. This can also be true of thicker cushioning once it is broken in. Wiker and Miller (1983) studied and reported on some of the specific effects of seat cushioning.

The frontal and sagittal plane models of human body masses were placed into the model as shown in **Figures 1** and **2**. Also inserted was the physical layout of a typical boat cross section and profile. In order allow valid comparison with the results from the previous study, the bow seat dimensions were essential unchanged. The starting point for the computer software model, then, was something that ultimately looked like **Figures 3** and **4**. Project constraints did permit testing of all the typical occupant postures. The posture shown in the figures was chosen as best representative of typical postures.

The position of the boat hull with respect to time was calculated using filtered real boat accelerometer data. This position data dynamically drives the Working Model® simulation by determining the hull position and orientation on the screen with respect to time. The changing hull positions put multi-axes forces on the human model. Such forces are then what cause the human model to dynamically respond with these movements then visually portrayed on the monitor. This yielded the ultimate results which allowed the project to achieve its objectives.

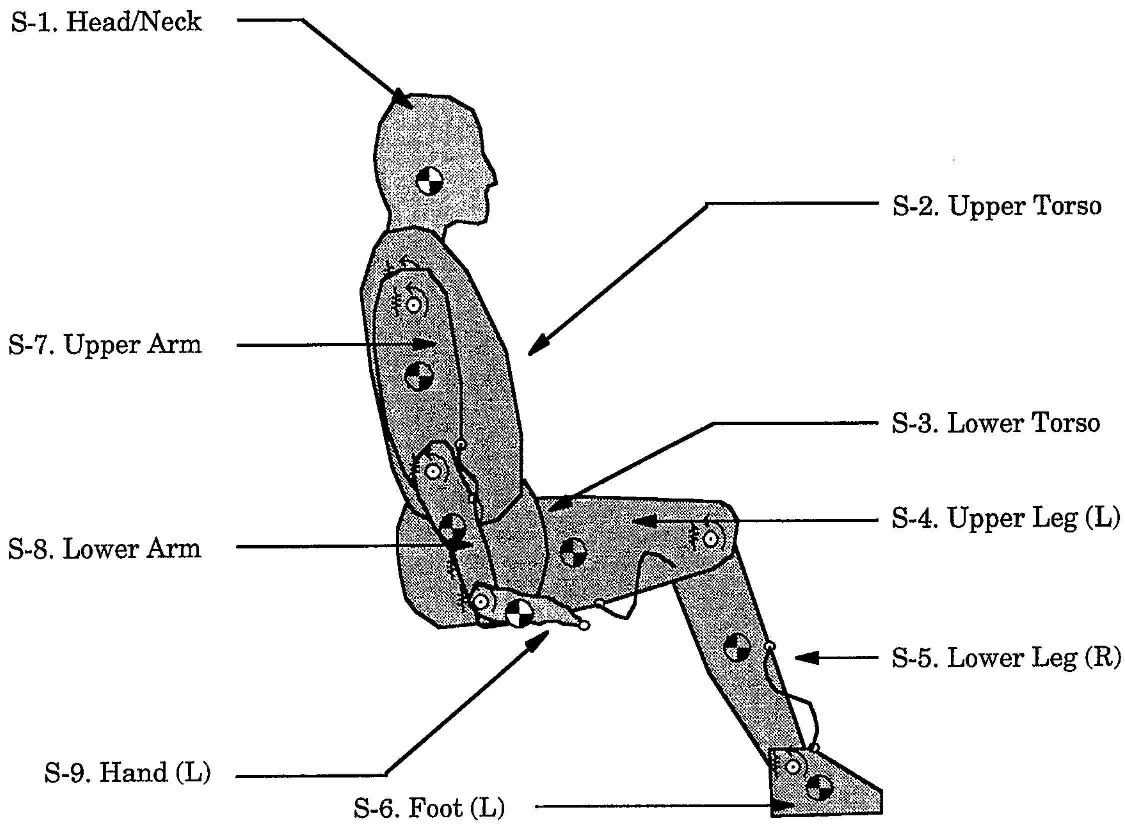


Figure 1: Segmented Sagittal (Side) Plane Model of Human Body

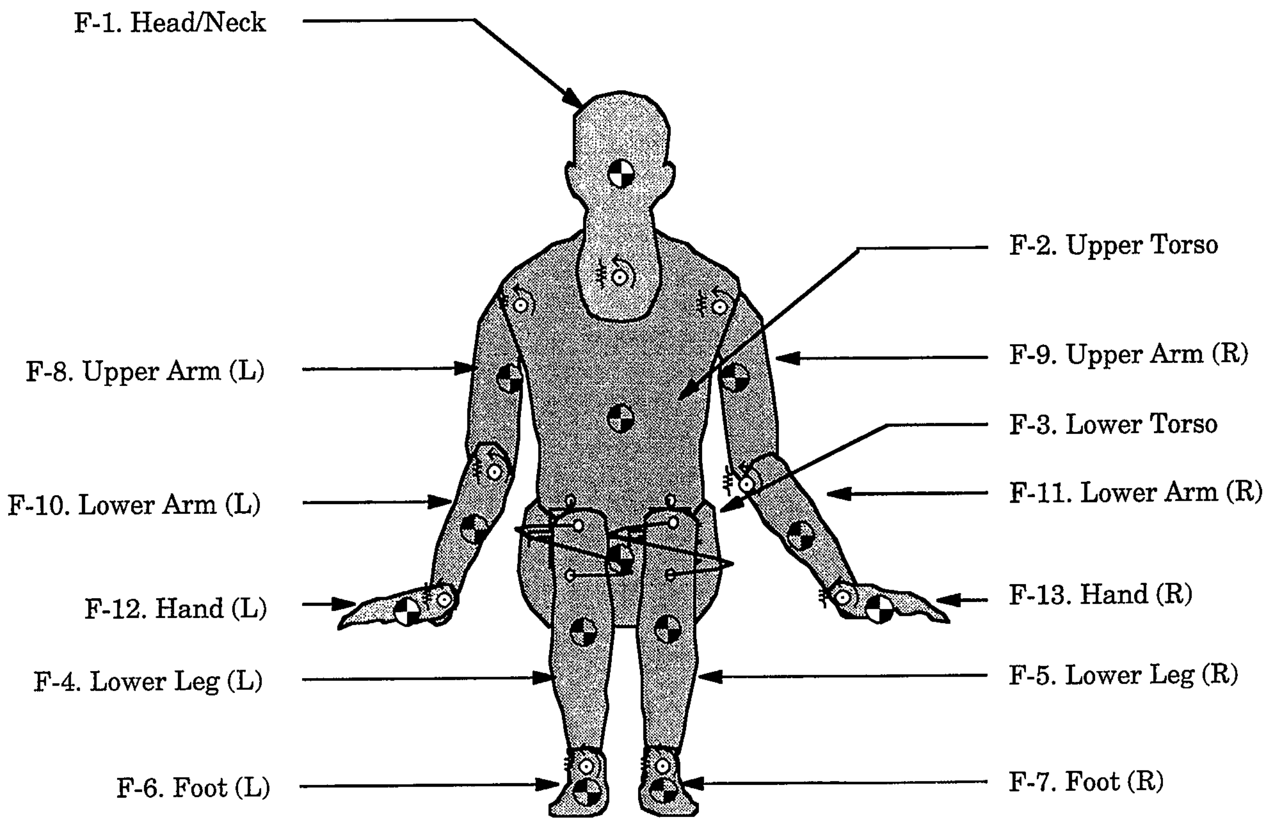


Figure 2: Segmented Frontal Plane Model of Human Body

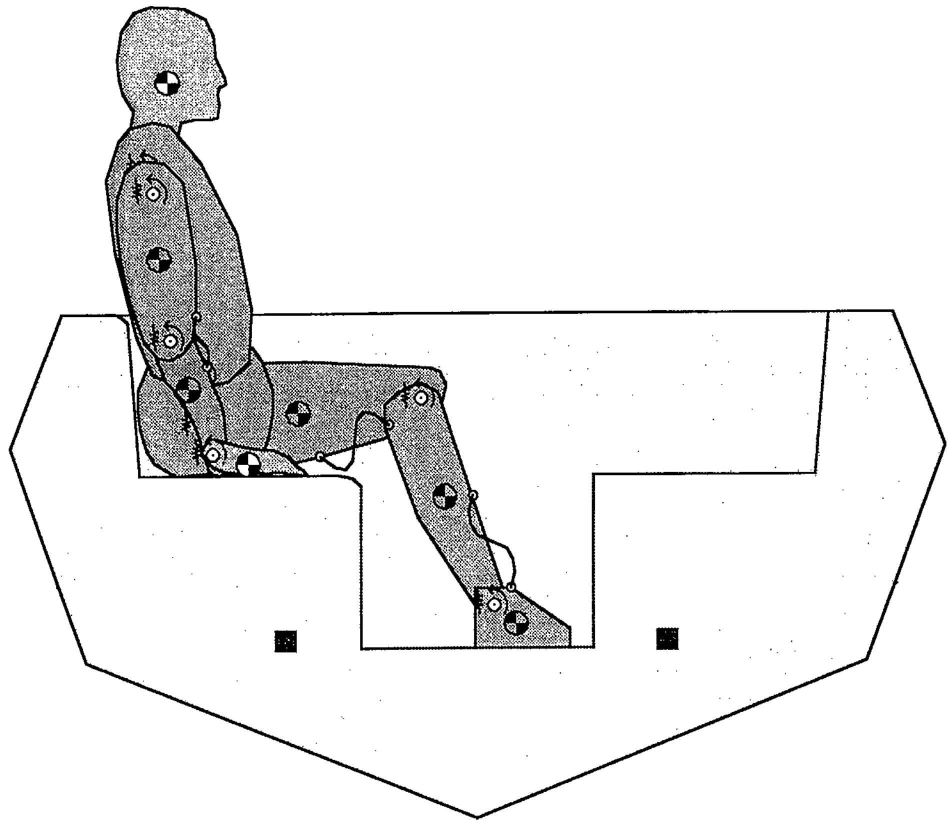


Figure 3: Transverse Section Through Occupant and Accelerometer Locations

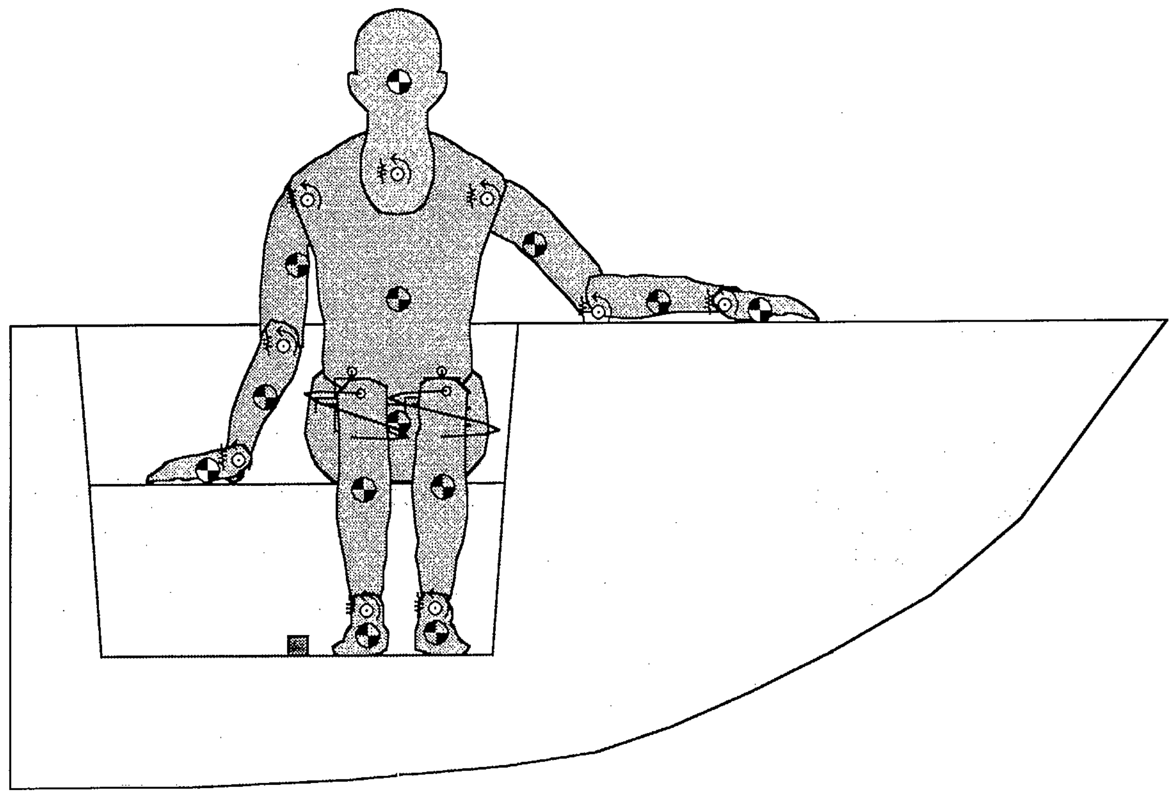


Figure 4: Profile View Through Occupant and Accelerometer Locations

Table 2: Spreadsheet of Working Model® Variables

No.	Name	Description	M (lb)	XCG (in)	YCG (in)	ø (deg)	Vx	Vy	Vø	I (lb-in^2)	L(in)	K (in-lb/°)	C(lb-sec/°)
S-1	Body[79]	Head/Neck	13.7	-24	36	-6	0	0	0	859	-	-	-
S-2	Body[123]	Upper Torso	35.9	-23	22	13	0	0	0	2664	-	-	-
S-3	Polygon #5	Lower Torso	40.4	-22	24	4	0	0	0	434	-	-	-
S-4	Polygon #5	Upper Leg	32.6	-16	13	91	0	0	0	1219	-	-	-
S-5	Polygon #2	Lower Leg	15.2	-3	8	22	0	0	0	408	-	-	-
S-6	Polygon #20	Foot	4.6	4	-3	-60	0	0	0	25	-	-	-
S-7	Polygon #31	Upper Arm	9	-24	22	-133	0	0	0	730	-	-	-
S-8	Polygon #36	Lower Arm	5.4	-22	15	18	0	0	0	149	-	-	-
S-9	Polygon #23	Hand	2	-18	9	75	0	0	0	22	-	-	-
S-10	Constraint [93] Pin Joint	Neck Joint	0	-25	31	-	0	0	0	0	-	40	0.4
S-11	Constraint[111]	L5/S1	0	-21	16	-	0	0	0	0	-	100	1
S-12	Constraint [112] Pin Joint	Hip Joint	0	-21	12	-	0	0	0	0	-	100	1
S-13	Constraint [130] Pin Joint	Knee Joint	0	-4	14	-	0	0	0	0	-	100	1
S-14	Constraint [89] Pin Joint	Ankle Joint	0	1	-1	-	0	0	0	0	-	5	0.05
S-15	Constraint [115] Pin Joint	Shoulder Joint	0	-25	30	-	0	0	0	0	-	5	0.05
S-16	Constraint [137] Pin Joint	Elbow Joint	0	-24	18	-	0	0	0	0	-	3	0.03
S-17	Constraint [140] Pin Joint	Wrist Joint	0	-20	10	-	0	0	0	0	-	2	0.02
S-18	Constraint 84] Rope	Knee Joint	0	-	-	-	0	0	0	0	9	-	-
S-19	-- Point [77]	Endpoint 1	0	-12	10	-	0	0	0	0	-	-	-
S-20	-- Point [80]	Endpoint 2	0	-7	12	-	0	0	0	0	-	-	-
S-21	Constraint [29] Rope	Ankle Joint	0	-	-	-	0	0	0	0	8.5	-	-
S-22	-- Point [26]	Endpoint 1	0	0	7	-	0	0	0	0	-	-	-
S-23	-- Point [27]	Endpoint 2	0	3	0	-	0	0	0	0	-	-	-
S-24	Constraint [118] Rope	Elbow Joint	0	-	-	-	0	0	0	0	4	-	-
S-25	-- Point [45]	Endpoint 1	0	-22	20	-	0	0	0	0	-	-	-
S-26	-- Point [81]	Endpoint 2	0	-21	-17	-	0	0	0	0	-	-	-
F-1	Body [76]	Head/Neck	13.7	0	41	0	0	0	0	860			
F-2	Body [89]	Upper Torso	35.9	0	28	0	0	0	0	3215	-	-	-
F-3	Body [97]	Lower Torso	73	0	28	0	0	0	0	644	-	-	-
F-4	Body [44]	Lower Leg (Left)	7.6	-3	12	-3	0	0	0	606	-	-	-
F-5	Body [79]	Lower Leg (Right)	7.6	-3	12	-3	0	0	0	606	-	-	-
F-6	Body [42]	Foot (L)	2.3	-3	2	0	0	0	0	55	-	-	-
F-7	Body [68]	Foot (R)	2.3	3	2	0	0	0	0	55	-	-	-
F-8	Body [41]	Upper Arm (L)	4.5	-8	30	-366	0	0	0	366	-	-	-
F-9	Body [81]	Upper Arm (R)	4.5	10	31	44	0	0	0	366	-	-	-
F-10	Body [30]	Lower Arm (L)	2.7	-11	20	-378	0	0	0	150	-	-	-
F-11	Body [77]	Lower Arm (R)	2.7	20	27	277	0	0	0	150	-	-	-
F-12	Body [35]	Hand (L)	1	-15	14	434	0	0	0	20	-	-	-
F-13	Body [37]	Hand (R)	1	28	26	286	0	0	0	20	-	-	-
F-14	Constraint [49] Pin Joint	Neck Joint	0	0	36	-	0	0	0	0	-	30	0.3
F-15	Constraint [144]	L5/S1	0	-	-	-	0	0	0	0	5	400	4
F-16	-- Point [142]	Endpoint 1	0	-4	21	-	0	0	0	0	-	-	-
F-17	-- Point [143]	Endpoint 2	0	-4	16	-	0	0	0	0	-	-	-
F-18	Constraint [66]	L5/S1	0	-	-	-	0	0	0	0	5	400	4
F-19	-- Point [64]	Endpoint 1	0	3	21	-	0	0	0	0	-	-	-
F-20	-- Point [65]	Endpoint 2	0	3	16	-	0	0	0	0	-	-	-
F-21	Constraint [141] Pin Joint	Ankle Joint (L)	0	-3	4	-	0	0	0	0	-	5	0.05
F-22	Constraint [144] Pin Joint	Ankle Joint (R)	0	3	4	-	0	0	0	0	-	5	0.05
F-23	Constraint [55] Pin Joint	Shoulder Joint (L)	0	-7	64	-	0	0	0	0	-	5	0.05
F-24	Constraint [71] Pin Joint	Shoulder Joint (R)	0	7	34	-	0	0	0	0	-	5	0.05
F-25	Constraint [52] Pin Joint	Elbow Joint (L)	0	-9	23	-	0	0	0	0	-	5	0.05
F-26	Constraint [85] Pin Joint	Elbow Joint (R)	0	15	26	-	0	0	0	0	-	5	0.05
F-27	Constraint [60] Pin Joint	Wrist Joint (L)	0	-12	15	-	0	0	0	0	-	5	0.05
F-28	Constraint [94] Pin Joint	Wrist Joint (R)	0	25	26	-	0	0	0	0	-	5	0.05
F-29	Constraint [26] Rope	Upper Leg	0	-	-	-	0	0	0	0	17	-	-
F-30	-- Point [1]	Endpoint 1	0	-3	16	-	0	0	0	0	-	-	-
F-31	-- Point [2]	Endpoint 2	0	-3	20	-	0	0	0	0	-	-	-
F-32	Constraint [87] Rope	Upper Leg	0	-	-	-	0	0	0	0	17	-	-
F-33	-- Point [84]	Endpoint 1	0	3	16	-	0	0	0	0	-	-	-
F-34	-- Point [86]	Endpoint 2	0	3	20	-	0	0	0	0	-	-	-

RESULTS

The determination of whether it was likely that a seated occupant would become unseated or not was made on the basis of the results of many runs using Working Model® simulations. As independent variables, type of boat maneuver and backrest height were used with the possible discrete results being subjectively classified as ejection, containment, or marginal. Boat maneuver was at two levels: hard turn and wake crossing; and seat backrest height was at three levels: six, nine, and twelve inches (See **Appendix C**). **Table 3** lists the results of the simulations for the hard turn runs containing the highest 25 percent lateral accelerations. In what might be surprising to the reader, the wake crossing maneuvers did not generate lateral accelerations of the magnitude needed to eject an occupant at any backrest height.

Table 3: Computer Simulation Results

Backrest Height (in.)	Result (Wake Crossing)	Result (Hard Turn)
6	Containment	Ejection
9	Containment	Marginal
12	Containment	Containment

Figures 5 and **6** are visual depictions of two example simulation hard turn runs, one using the twelve inch backrest height, and one using the six inch backrest height. **Figure 5** is a series of sequential frames representing a simulation run in which the boat occupant model was contained, and **Figure 6** is a series of sequential frames representing a simulation run in which the boat occupant model was ejected. In **Figure 6,** only the "more interesting" sagittal plane view is shown after the first frame.

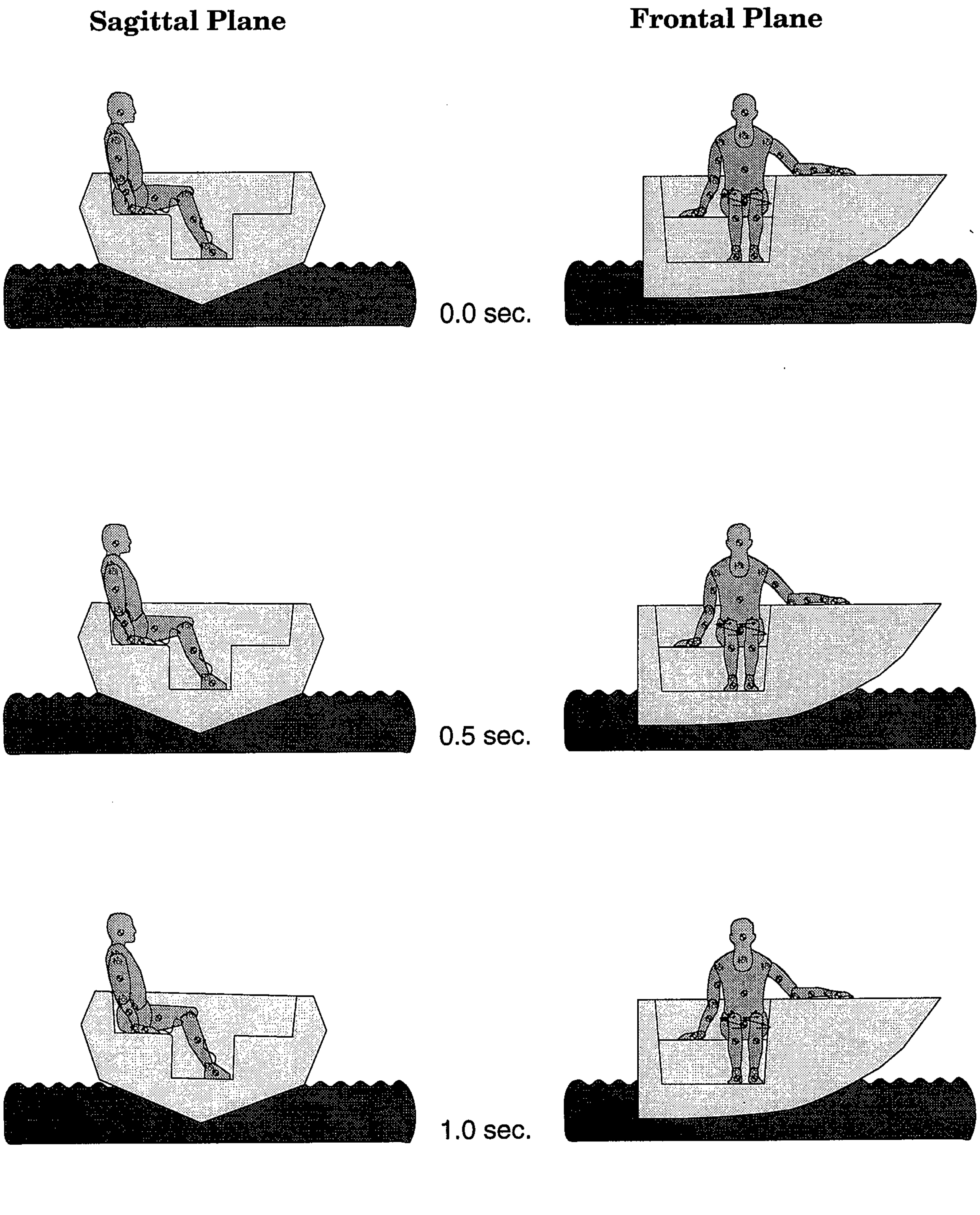


Figure 5: Sample Working Model® Simulation Run (12" backrest)

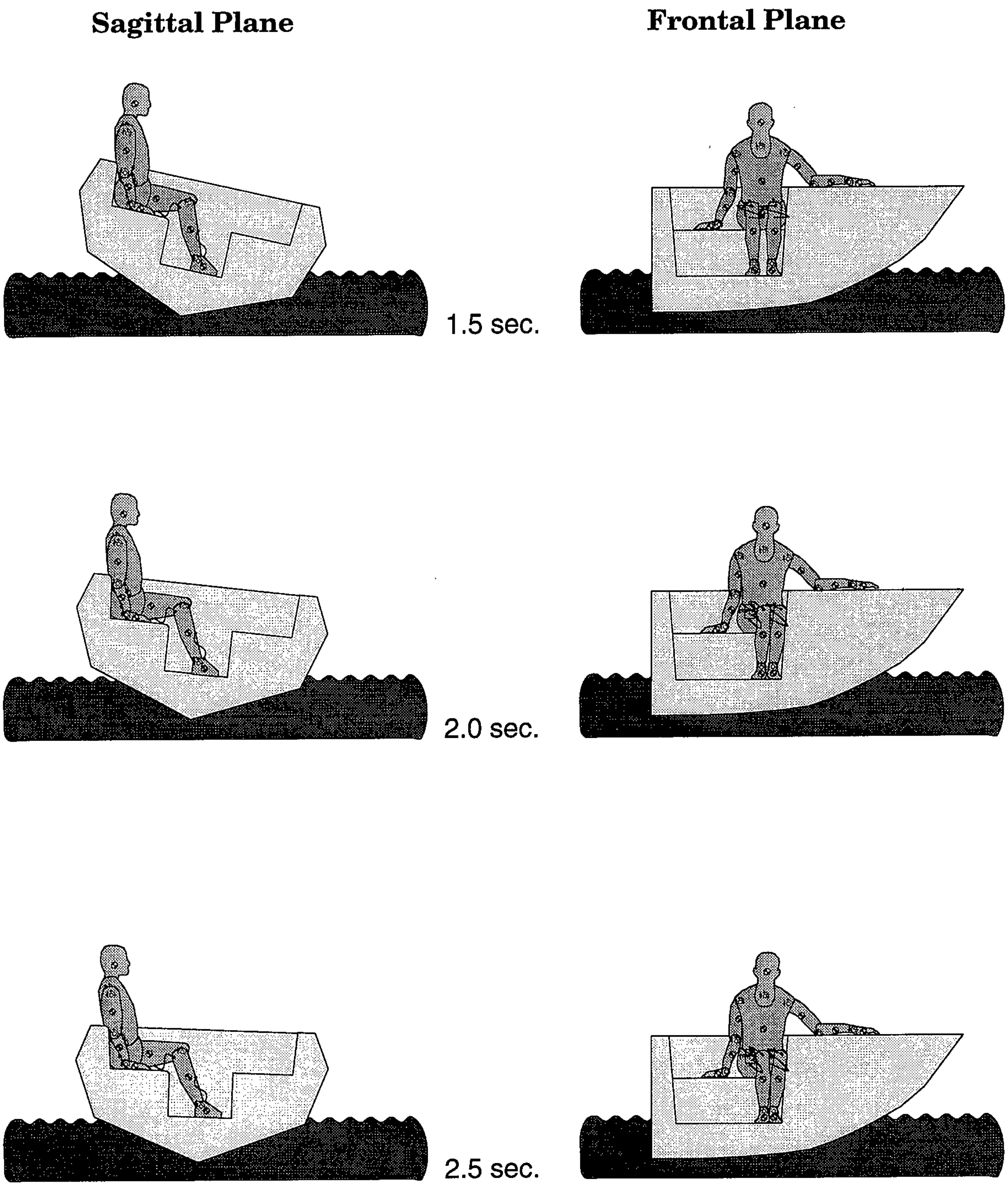


Figure 5: (continued)

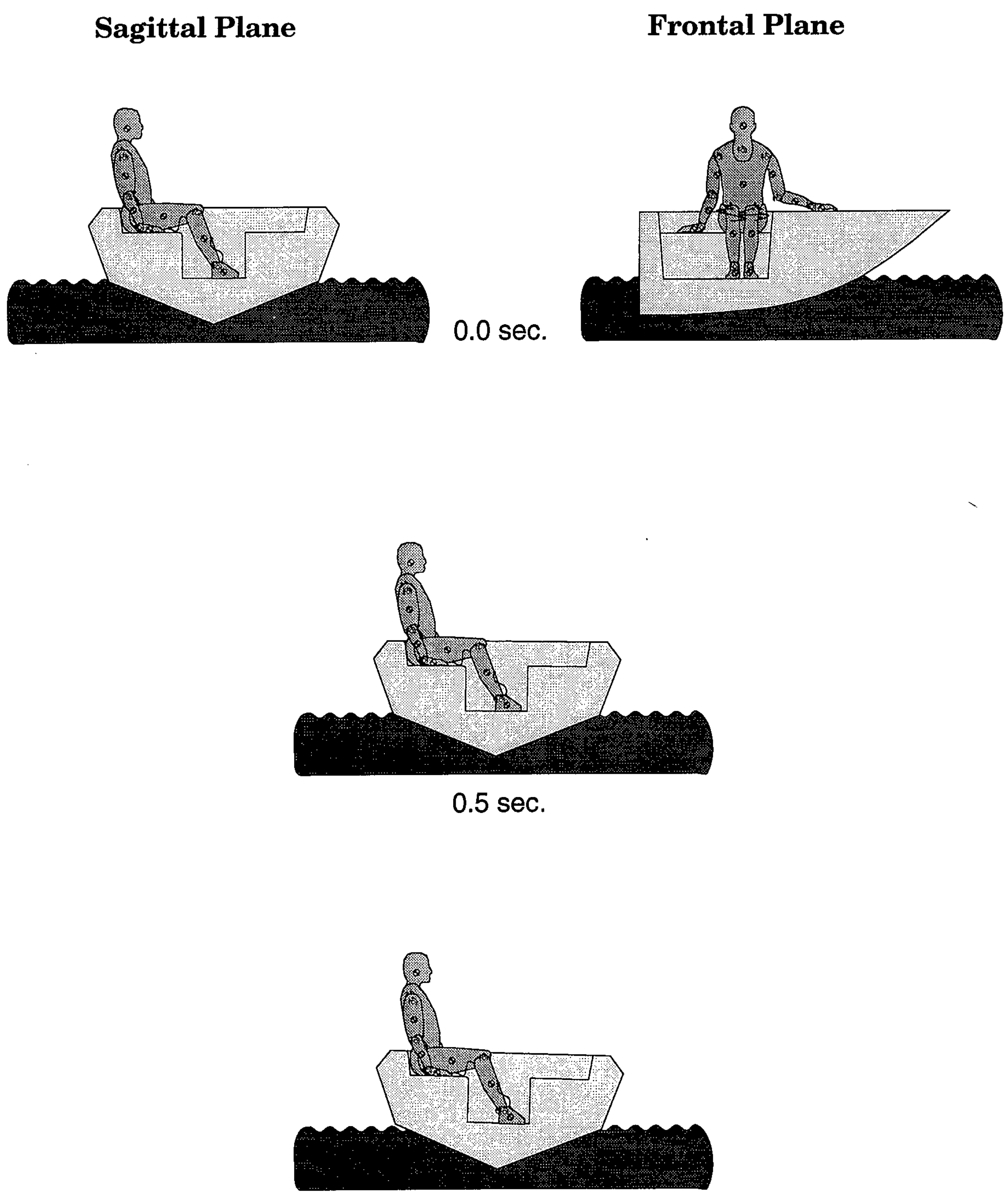
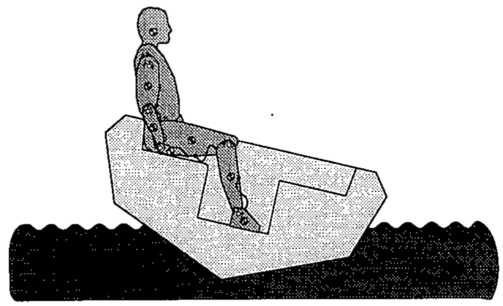


Figure 6: Sample Working Model® Simulation Run (6" backrest)



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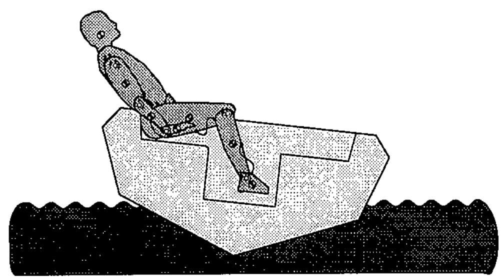

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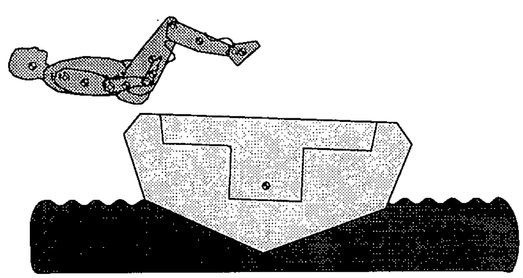


2.5 sec.

Figure 6: (continued)

SUMMARY OF CONCLUSIONS

The implicit objective of this study was to explore the feasibility of developing and demonstrating an enhanced human/boat model. This is a model which could mathematically simulate and computer graphically illustrate what might be dynamically happening to occupants riding in a low backrest boat seat. The results of this enhanced model would then be compared to our earlier results which were determined by using both a more simplified model and a more simplified input data set.

Somewhat surprising, this preliminary human/boat model utilized in the earlier study, while having a lower level of fidelity, was a fairly reasonable predictor of occupant containment as defined in this latter report. Our earlier on-water boat acceleration data in combination with the enhanced computer simulation approach developed herein served to verify the results we approximated by more crude means in our previous study (Miller, Grieser, and Clark, 1996). Namely, that there are maneuvers even in relatively calm water for which boats with a six inch (or lower) backrest may lead to passenger dislocation. Also confirmed was the finding that the backrest twelve inch and higher appears adequate to contain our simulated passenger even under hard turn type maneuvers. The nine inch backrest, though an improvement over the six inch backrest, still did not result in containing our simulated boat occupant under all conditions evaluated. The nine inch backrest would, thus, have to be considered as "marginal," awaiting further testing.

Not only are the results from the present study useful for preliminary predictions of bowrider ejection, but the methodology developed can now be used for a more detailed analysis of many different combinations of backrest configurations and occupant postures.

This dynamically driven computer model for preliminary predictions of bowrider ejection would also be useful in the evaluation of dynamic boat/human interactions that are very different from seat and passenger ejection issues.

DISCUSSION AND OTHER CONTAINMENT FACTORS

Effect of Untested Factors on Results

Introduction

While we are not certain of all the factors which play a role in occupant ejections, we would estimate that as much as 75 percent could be attributed to backrest height. Consequently, this has been the focus of these studies. There are factors outside the scope of this study which were not tested, yet may have a potentially significant effect on occupant containment and are therefore worth mentioning (**Figure 7**). Some of these factors include: presence and height of railings, seat backrest angle, boat roll angle, handhold availability and use, presence and geometry of foot wells, occupant anthropometry, occupant posture, foothold availability and use, slip resistance between the person and the boat seat, and occupant awareness. Further research may uncover other factors that play a significant role in occupant containment.

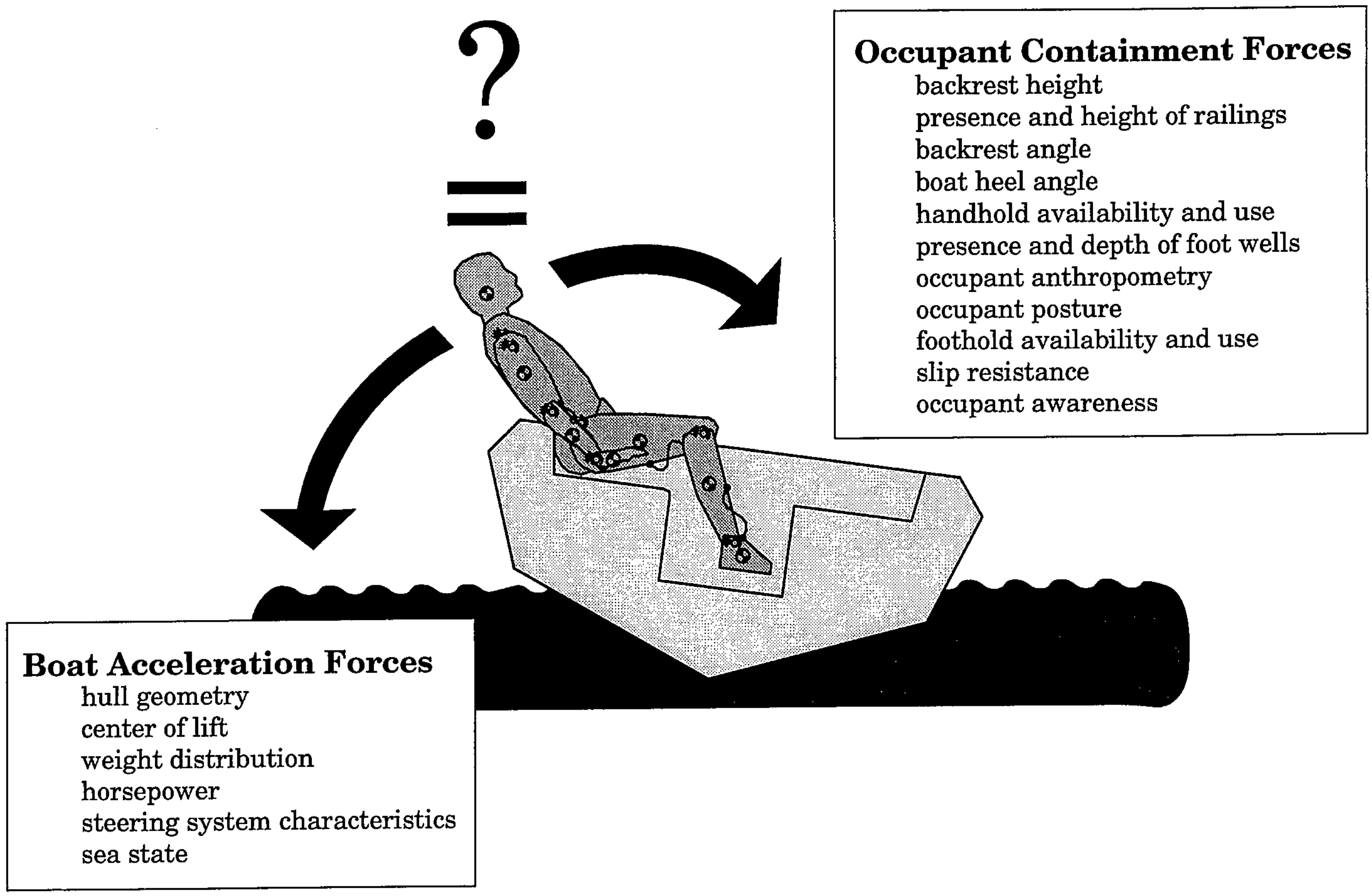


Figure 7: Occupant Containment/Boat Acceleration Force Factors

The effect of these factors (in addition to backrest height, of course) on the probability of occupant containment could be mathematically modeled. Multiple regressions of experimental data from testing the effects of these occupant containment factors could result in a predictive equation for occupant containment. A simplified form of such an equation follows:

$$\text{Occupant Containment Probability} = \sum_{i=1}^{n} V_i \times W_i$$

for n occupant containment factors

where:

V_i = Indicator variable (0 or 1)

W_i = factor weighting

Every occupant containment factor has a indicator variable (V_i), which indicates whether a particular factor is present. For example, the indicator variable takes on a value of "1" if a boat has a railing at the top of the backrest and "0" if not.

The factor weighting (W_i) represents an experimentally determined magnitude change in occupant containment probability attributed to a particular factor level. The factor weighting values increase as a factor level increases the occupant containment probability. For example, if the weighting value for a three inch high railing mounted at the top of the backrest is 0.10, one would expect this value to be greater for increased railing heights (up to a reasonable limit, of course) because the probability of the occupant being contained would be greater. Therefore, the weighting value might be 0.15 for a four inch railing versus 0.10 for the three inch railing. Weighting values are negative for factor levels that decrease the occupant containment probability.

Table 4 shows typical expected indicator variables values and factor weightings for each factor in the occupant containment prediction equation. For purposes of simplicity, factor interactions are not included in the table.

Table 4: Occupant Containment Prediction Equation

$$\text{Occupant Containment Probability} = \sum_{i=1}^{n} V_i \times W_i$$

Factor (i)	Potential Indicator Variable (V_i) Value(s)	Weighting (W_i)
Backrest Height	1: if backrest exists 0: if no backrest	Increases with increasing backrest height
Railings: Presence and Height Above Backrest	1: if railing exists 0: if no railing	Increases with increasing railing height
Backrest Angle	1: if backrest exists 0: if no backrest	Decreases with increasing backrest angle (toward horizontal)
Boat Roll Angle	1: for roll angles toward turn center 0: if roll angle = 0 -1: for roll away from turn center	Increases with increasing roll during turn
Handholds: Availability and Use	1: if handhold available and used 0: if no handhold or not in use	Variable
Foot Wells: Presence and Geometry	1: if foot well exists 0: if no foot well	Increases with increasing foot well depth and decreasing width (generally)
Occupant Anthropometry	1: (always)	Decreases with increasing vertical center of gravity height
Occupant Posture	1: (always)	Increases for postures with decreasing vertical center of gravity height and increasing rotational moment of inertia
Footholds: Availability and Use	1: if footholds available and used 0: if no footholds or not in use	Variable
Slip Resistance	1: (always)	Increases with increasing slip resistance between occupant and seat/boat
Occupant Awareness	1: if occupant aware of impending maneuver 0: if surprise	Increases with increasing occupant awareness
Lateral Acceleration Exposure	-1: (always)	Increases with increasing acceleration exposure

To use the occupant containment probability equation, one needs to choose the appropriate indicator variable (V_i) from the second column of **Table 4** for each of the factors, multiply them by each factor's weight (W_i), and then total the weights.

For example, consider a boat with a backrest, railing, and foot well, which rolls toward the turn center and is about to perform a "surprise" maneuver. The appropriate full equation would be:

$$\begin{aligned}&\textit{Occupant containment probability} = (1\times W_{Backrest\ Height}) + (1\times W_{Railing}) +\\&(1\times W_{Backrest\ Angle}) + (1\times W_{Boat\ Heel\ Angle}) + (0\times W_{Handholds}) + (1\times W_{Footwells}) + (1\times W_{Anthropometry}) +\\&(1\times W_{Posture}) + (0\times W_{Footholds}) + (1\times W_{Slip\ resistance}) + (0\times W_{Awareness}) + [(-1)\times W_{Acceleration}]\end{aligned}$$

Of course, this equation cannot be solved until the weights (W_i) are experimentally determined. Until such time, the following sections have been included to describe qualitatively how these factors affect the needed backrest height to maintain an adequate occupant containment probability.

Presence and Height of Railings

The computer boat model used for this study did not have railings. Certain railing designs can act to decrease the required backrest height. For example, the **Figure 8** sequence portrays hypothetically a computer simulation run with a nine inch backrest and a three inch high railing for a total effective backrest height of twelve inches. We would anticipate the same results, that is, the occupant would be contained just as if the occupant was leaning against a 12 inch backrest (compare **Figure 8** to **Figure 5**).

For a railing design to be considered a component of the total effective backrest height, we would propose the following criteria:

1) the railing(s) shall be located near or at the same plane formed by the backrest extended upward,
2) the railing(s) shall be long enough to extend above the full width of the backrest locations,
3) the railing(s) shall make up less than 50 percent of the total effective backrest height (unless there are no openings under the railing), and
4) the railing(s) shall comply with the ABYC H-41 requirements for "handhold devices."

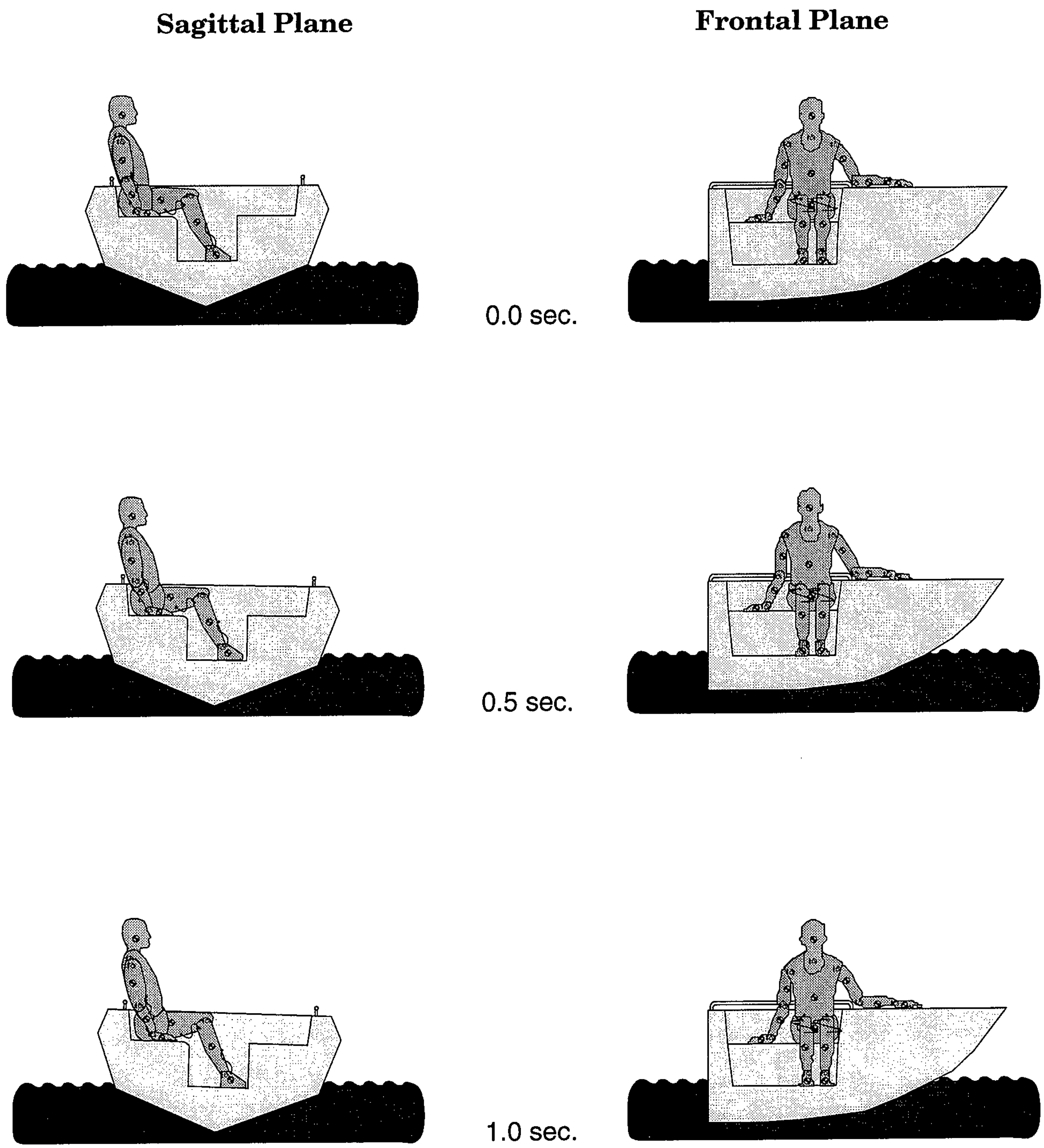


Figure 8: Hypothetical Simulation Run (9" backrest, 3" railing)

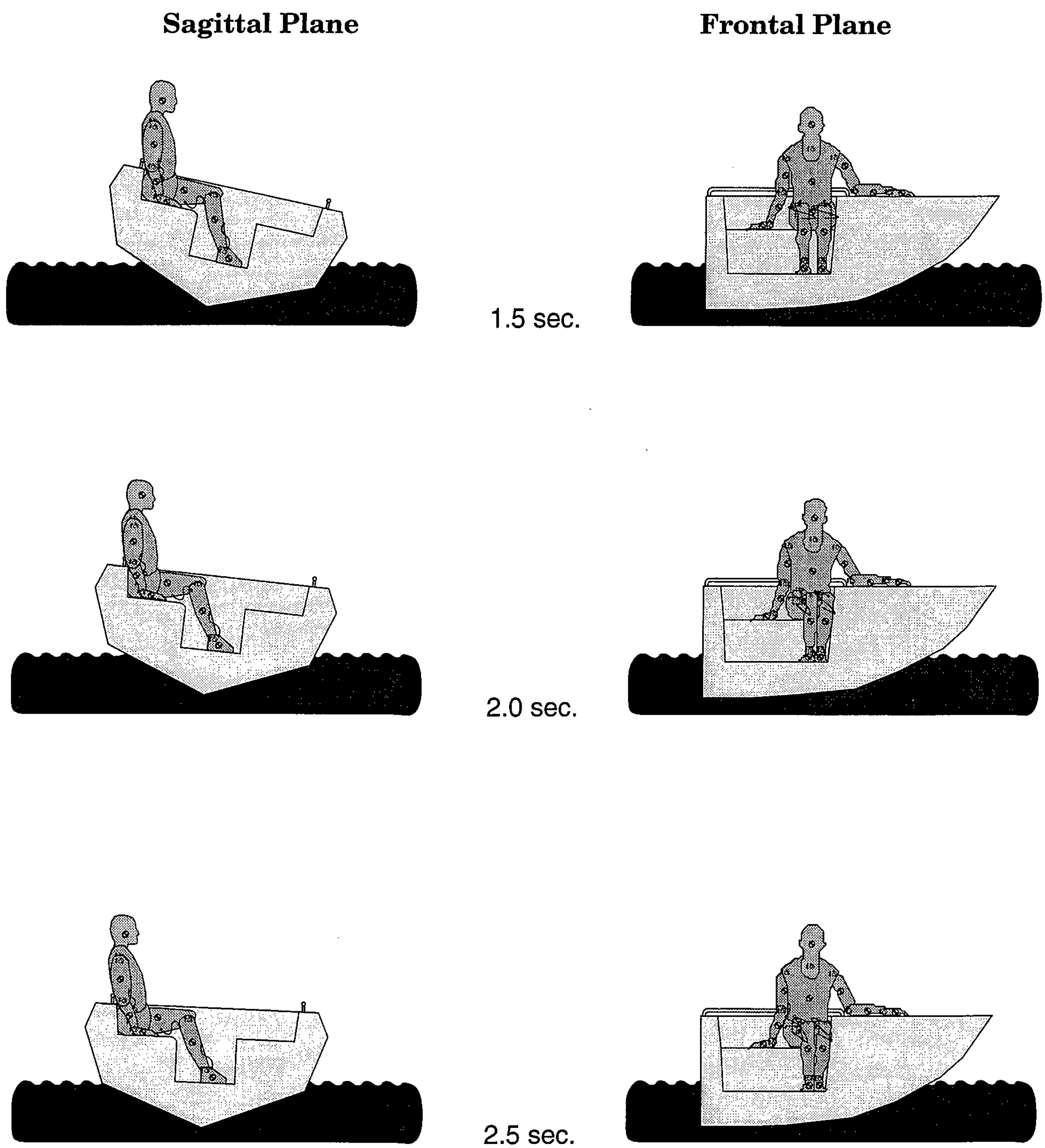


Figure 8: (continued)

Seat Backrest Angle
The seat backrest angle tested in the current model was 5 degrees relative to vertical (**Figure 9**). As this angle increases, a greater proportion of the total accelerative force experienced by the occupant acts to slide the occupant up the backrest (versus acting to force the occupant directly against the backrest) making ejection more likely. Therefore, as the backrest angle <u>increases</u>, the required backrest height needed to contain an occupant can also <u>increase</u>.

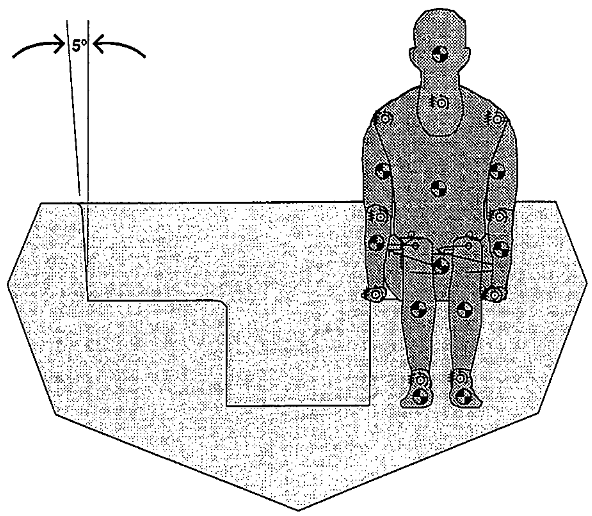


Figure 9: Seat Backrest Angle/Alternate Bow Occupant Posture

Boat Roll Angle
The backrest height required to contain an occupant is also dependent on the boat roll angle during lateral acceleration. As roll angle increases toward the center of the turn circle, a greater proportion of the accelerative force is acting into the seat pan rather than against the backrest. Therefore, the <u>greater</u> the roll angle (toward the turning circle center) during a turning maneuver, the <u>less</u> backrest height required for occupant containment. The subject test boats' roll angles were not directly measured during the on-water accelerometer data gathering. However, roll angle was calculated from the accelerometer data and recorded during all computer simulation runs: the average maximum roll angle during substantial lateral accelerations was approximately 12 degrees.

Planing hulls typically roll toward the center of the turning circle. For the relatively infrequent exceptions in which this is not true (such as a boat that "hooks the chine" or bow steers when plunging into a wave), <u>increased</u> roll angle away from the center of the turning circle would <u>decrease</u> the occupant containment probability for a given acceleration exposure.

Handhold Availability and Use
There are many variables affecting the degree to which handhold use will help contain an occupant. Miller and Grieser (1998) and Miller, Grieser, and Clark (1996) studied and reported on boat handhold design and use.

Presence and Geometry of Foot Wells
As shown in **Figure 3**, the boat model featured a foot well which allowed a human model posture similar to that of the typical human seated position with feet on the floor with the opposite side of the well near enough to provide a surface against which an occupant can brace his or her feet. The alternative configuration is no foot well. In that case, the occupant's legs and feet would be no lower than the lower torso, which would raise the occupant's vertical center of gravity. The higher the occupant's center of gravity, the more likely that ejection will occur. The foot wells also may provide areas against which an occupant can "lock" his or her legs and/or feet to help prevent ejection. How effectively an occupant can do this depends on his or her anthropometry relative to the footwell geometry. Generally the less width, or "knee room," the more likely it is that an occupant of a given stature can lock his or her legs in the well.

Occupant Anthropometry
The human model used for this study was designed to closely match 50th percentile male anthropometry. People with larger statures usually have higher vertical centers of gravity and therefore have greater backrest height requirements. However, the authors recognize that, for a variety of reasons, typical bowrider occupants often consist of children and smaller adults (especially in smaller boats having six to twelve inch backrests), and therefore a 50th percentile male human model might be considered "extreme enough" for our purposes. If it is desired to apply these recommendations for backrests to other seating areas in boats, then the minimum backrest height should probably be increased to accommodate adults with larger statures (e.g. 99th percentile male, which has a seated vertical center of gravity location approximately 2-3 inches above that of a 50th percentile male).

Occupant Posture
Project constraints did not permit modeling of all the typical occupant postures. The posture shown in earlier figures was chosen during the previous study as best representative of typical postures under the limitations of 1) a two dimensional dynamic simulation and 2) the available biomechanical data.

Another common bow occupant posture is shown in **Figure 9** where the occupant faces forward. The body in this posture would be somewhat less resistant to rotation over the boat's gunwale which would increase the backrest height requirements slightly. It is possible under these conditions that a nine inch backrest might become unacceptable while the twelve inch backrest would maintain its adequacy, but by a lesser margin.

Foothold Availability and Use
These authors have not studied the variables affecting the degree to which foothold use will help contain an occupant, although many of the same basic handhold design principles may apply.

Slip Resistance
For our purposes, slip resistance can be defined as the resistance to motion attributed to frictional forces between the occupant and boat. In this study, slip resistance was considered negligible. Adding slip resistance would decrease the needed backrest height.

Occupant Awareness
The "surprise factor" may be one of the most important occupant containment factors because of its strong interactions with other factors. That is, an occupant's awareness of an impending boat maneuver likely affects the probability that the occupant will change his or her posture, if necessary, and use handholds and footholds.

Lateral Acceleration Exposure
The lateral acceleration to which an occupant is exposed during a turning maneuver, or centripetal acceleration (a_c), is represented by the following equation:

$$a_c = \frac{v_t^2}{r}$$

where:

v_t = the boat's tangential velocity (or forward speed)

r = the boat's turning radius

The tangential velocity and turning radius capabilities of a boat are dependent on its hull geometry (including fins and other appendages), center of lift, weight distribution, horsepower, steering system characteristics, and the sea state.

Falls Overboard and Future Regulations

That such an enhanced human/boat model could be developed and quantified we believe has been unequivocally demonstrated by this and the previous related study. One then has to ask the questions: "What next?" and "Why?" Of more significance is the "Why?" question: "Why go further in trying to use such a model?" and "What objectives might be achieved by proceeding with yet further studies in this direction?" Lest the end objective be lost sight of, our ultimate goal was to determine if there was a design tool or methodology which could be developed to assist manufacturers in improving the level of occupant seating safety designed into their vessels. The particular feature explored with the present study was seat backrest height as one very significant seat design factor in occupant containment. Such containment is likely related ultimately to that portion of boating fatality data identified by "falls overboard" as a substantial overall factor leading to such fatalities.

One question which these present studies seemed to positively conclude is that backrest height is a factor in the potential for occupant falls overboard. We recognize that none of the data available is refined enough to identify what percent of falls overboard occur from an occupant's seated position. However, for whatever falls do occur from seats, the height of the supporting structure around the occupant would likely play a critical role. Such findings as ours could promote the same methodology being applied to other boat seating areas.

Even without further testing, it can be recommended to the Coast Guard that seat height in general, and bowrider backrest height in particular, be treated as an occupant protection safety concern. For bowrider backrests, this study has given some fairly firm results at the extremes (six inches and twelve inches). It has not given a definitive answer for the backrest heights in between (except that nine inches may still be marginal under certain conditions). It also has not addressed the previously discussed ten other factors which will play a role in the tendency for falls overboard initiating at the seat back.

The Coast Guard's interest in the backrest height factors could lead to either further research or some "Advance Notice of Proposed Rulemaking" to stimulate more research in the area on the part of private manufacturers. Whether future regulations would also be of a "performance" standard type or "design" standard type is an issue which can be answered by future research.

Future Research

Evaluating Other Occupant Containment Factors

It must be emphasized that the present study would still have to be considered a "demonstration project." While successful to this point, neither the amount of actual data generated nor the breadth of factors covered could be considered as sufficient scientific foundation from which firm recommendations to manufacturers or the Coast Guard could be made.

To get this additional quantitative data, the enhanced simulation model developed in this present study should be utilized to evaluate more configurations of the input variables which likely effect occupant containment. This would include the evaluation of: presence and height of railings, seat backrest angle, boat roll angle, handhold availability and use, presence and geometry of foot wells, occupant anthropometry, occupant posture, foothold availability and use, slip resistance between the person and the boat seat, and occupant awareness.

A Smarter "Dummy"

A key to the improved methodology lies in the added fidelity given to the human model used. In the "free" body model used previously, no attempt was made to include additional resistance to the acceleration forces which was acting upon it, beyond what was required to maintain the initial posture. It (the human model) was not trying to hold on, use a railing or handhold, or squeeze its legs and feet to increase the friction between them and the boat hull. This shortcoming could be critical to results, since the capability of any theoretical "dummy" or actual real person to utilize available handhold devices or other restraining measures could make even the marginal backrest heights acceptable and safe. While not evaluated as a part of the present study, our present enhanced simulation model is now capable of including these factors in any extension of this study.

The advantages of undertaking fairly extensive computer simulation evaluations over real-time, real-life experiments, have traditionally been **control** and **costs**. These advantages bring us to recommend such additional simulation in the present matter before proceeding to the higher fidelity testing described below. These computer simulation efforts can identify the minimum but most vital situations for which some more real life testing can then be done. Recall that we initially did real boat testing to obtain some our original dynamic force data for various style boats (**Appendix B**). This testing included controlled sharp turns (up to approximately 2 G after filtering), but higher G forces can be generated during "out of control" turn maneuvers involving chine catching or bow steering.

Higher Fidelity Testing

The results from an enhanced simulation methodology may seem very promising, especially in light of their close agreement with those in the simplistic conditions of the previous study. It would not be advisable for manufacturers to take the findings of this research and utilize only them for future design changes. It would also not be justified for the Coast Guard to immediately seize upon them for purposes of future regulations other than an Advanced Notice of Proposed Rulemaking. The reason is, of course, that strictly mathematical models are and should be suspect because of all the assumptions necessary to make them work.

Some believe that the usual biomechanical computer model assumptions which go along with simulations as was done in the present study need to be validated by anthropomorphic data, which is considered to have that higher fidelity. While we do not believe that any substantial difference in results would be expected; nonetheless, such validation studies may be justified if significant design or regulation decisions are to follow.

Anthropomorphic dummies are readily available and have their characteristics defined in accordance to SAE standards. They could be used with land-based "real" cockpit simulators driven by the acceleration data collected in our previous study, or they could be used on-the-water in real boats put through controlled maneuvers, as was done in our earlier study to collect acceleration data. Any such studies would unquestionably increase the fidelity of the experimental setting along with the resulting data.

Appendix A

References

Miller, J.M. and Grieser, B.C. "Boat Handhold Placement" *Occupant Protection Phase III*, Final Report to U.S. Coast Guard, July 1998.

Miller, J.M., Grieser, B.C., Clark, D.R. "Bowrider Backrest Height Variables: An Experimental and Simulation Study," *Occupant Protection Phase II*, DOTCG Grant No. 130202, NTIS PB96 195839XSP, Final Report to U.S. Coast Guard, February 1996.

Miller, J.M., Grieser, B.C., Clark, D.R. "Designs of Boat Handholds and Boarding Ladders: Principles and Examples," *Occupant Protection Phase II*, DOTCG Grant No. 130202, NTIS PB96 195839XSP, Final Report to U.S. Coast Guard, April 1996.

Miller, James M. and Wiker, Steven F., "Acceleration Exposures in Forward Seating Areas of Bowrider Boats", *Human Factors*, Vol. 25, No. 3, 1983.

Appendix B

Experimental Methodology

Accelerometer data was collected at approximate occupant seat locations during typical recreational boat maneuvering. Such acceleration data was in all three primary axes to cover the possibilities of forces which an occupant might experience.

In earlier days when these and some other researchers collected such data, it was a serious and sometimes insurmountable task to collect and reduce the necessary accelerometer data which could be used to address this hypothesis without hundreds of hours of manual data reduction. And then there may be no way of critically analyzing the data in a way to apply inferential statistics to arrive at any conclusions. However, with the evolution of higher power computers and increased portability, it is now possible to accomplish such tasks and to give meaningful interpretation to the millions of data points involved. To accomplish this effort, therefore, the latest computerized data collection and analyses equipment had to be purchased or leased. The equipment chosen is listed in the following paragraph.

<u>Test Equipment</u>

The following equipment was used in this study:

- The Miller Engineering Remote Data Acquisition System was developed to include the following test hardware and software:

    1) A laptop computer (Compaq LTE Elite)

    2) An SCXI modular data acquisition unit with A/D boards, multiplexing, and signal conditioning (National Instruments SCXI-1200, 1100, 1000DC)

    3) LabView data acquisition and analysis software (also by National Instruments)

- Two triaxial accelerometers (Bruel and Kjaer Model 4321)

- Six accelerometer charge amplifiers (Bruel and Kjaer Model 2635)

- A Wesmar SLM-33C Level Monitor

<u>On-the-Water Test Location</u>

To undertake the data collection effort it was necessary to select a lake on which there would be a minimum amount of variation and the least number of uncontrolled water perturbations. This criteria could be achieved at the OMC test facility located on Fox Lake, and OMC was generously cooperative in allowing the study to be performed using their facility, boats, and support staff. All tests for this endeavor, then, were performed from Oct. 2-13, 1995 at Fox Lake, a large public chain lake in Fox Lake, IL. The water depth varied from 3 to 7 feet in the area of the testing.

Test Boats

The selection of the particular boats to be tested was based on boat parameters which were compiled on about 300 recreational powerboats. Statistical regression analyses of these were done on the basis of such things as length, beam, weight, power rating, powering configuration, and hull material. The regression results revealed four general classes from which the test boats could reasonably be chosen. Weight, of course, was highly correlated with the other key parameters: length, beam, and hull material. The selection of specific boats to represent four stratified clusters was based on reasonable availability. These boats ultimately selected are shown in Table B-1.

Table B-1: Boats and Equipment

Test Boat No.	Length(ft)	Type	Hull	Material	Powering
1	20	Bowrider	Deep-vee	FRP	175 hp outboard
2	17	Fish-n-Ski	Semi-vee	FRP	115 hp outboard
3	14.5	Fishing boat	Semi-vee	Al	40 hp outboard
4	22	Deck boat	Semi-vee	Al	150 hp outboard
5 (wake generator)	25	Center Console	Deep-vee	FRP	Twin 225 hp outboards

Placement of Test Equipment

Two triaxial accelerometers were orthogonally mounted at bow occupant positions at the test boats' soles -- one port and one starboard. The exact accelerometer mounting locations were chosen based upon boat geometry, uniformity, and proximity to typical occupant seating locations. The specific accelerometer positions for each boat are shown in Figure B-1. Distances A and C for each craft are given in Table B-2.

The transducers were oriented according to the standard convention in naval architecture: the x-axis ran fore-aft with the positive direction being forward; the y-axis ran port-starboard with the positive direction being port; and the z-axis ran up and down with upward being the positive direction (Figure B-1). The raw signal output from the both of the accelerometer channels was amplified and filtered by three separate charge amplifiers. These charge amplifiers, housed in splash proof containers, were attached to the boat near each of the accelerometers. The entire Miller Engineering Remote Data Acquisition System was also housed in a splash proof container and mounted near each vessel's estimated center of gravity. The charge amplifiers' lower and upper frequency rejection limits were set at their lowest possible values, 0.2 Hz and 100 Hz, respectively. A programmable external mouse was mounted near the data acquisition equipment operator for easy remote triggering. See Figure B-1 for an example of the typical equipment layout used in each of the test boats. The amplified and filtered signals from each test run were then digitized, scaled programmatically, and stored in spreadsheet form on the Compaq laptop computer's hard drive.

The ultrasonic fluid level measuring device was extended approximately 3 feet off the end of a dock and suspended 5.5 feet above the mean water surface. The device's output signal is first amplified by its own preamplifier, and then digitized, scaled programmatically, and stored in spreadsheet form on the Compaq laptop computer's hard drive.

Table B-2: Accelerometer Layout Dimensions

Test Boat No.	Distance "A" (in.)	Distance "C" (in.)
1	66	30
2	63	30
3	65	30
4	78	56

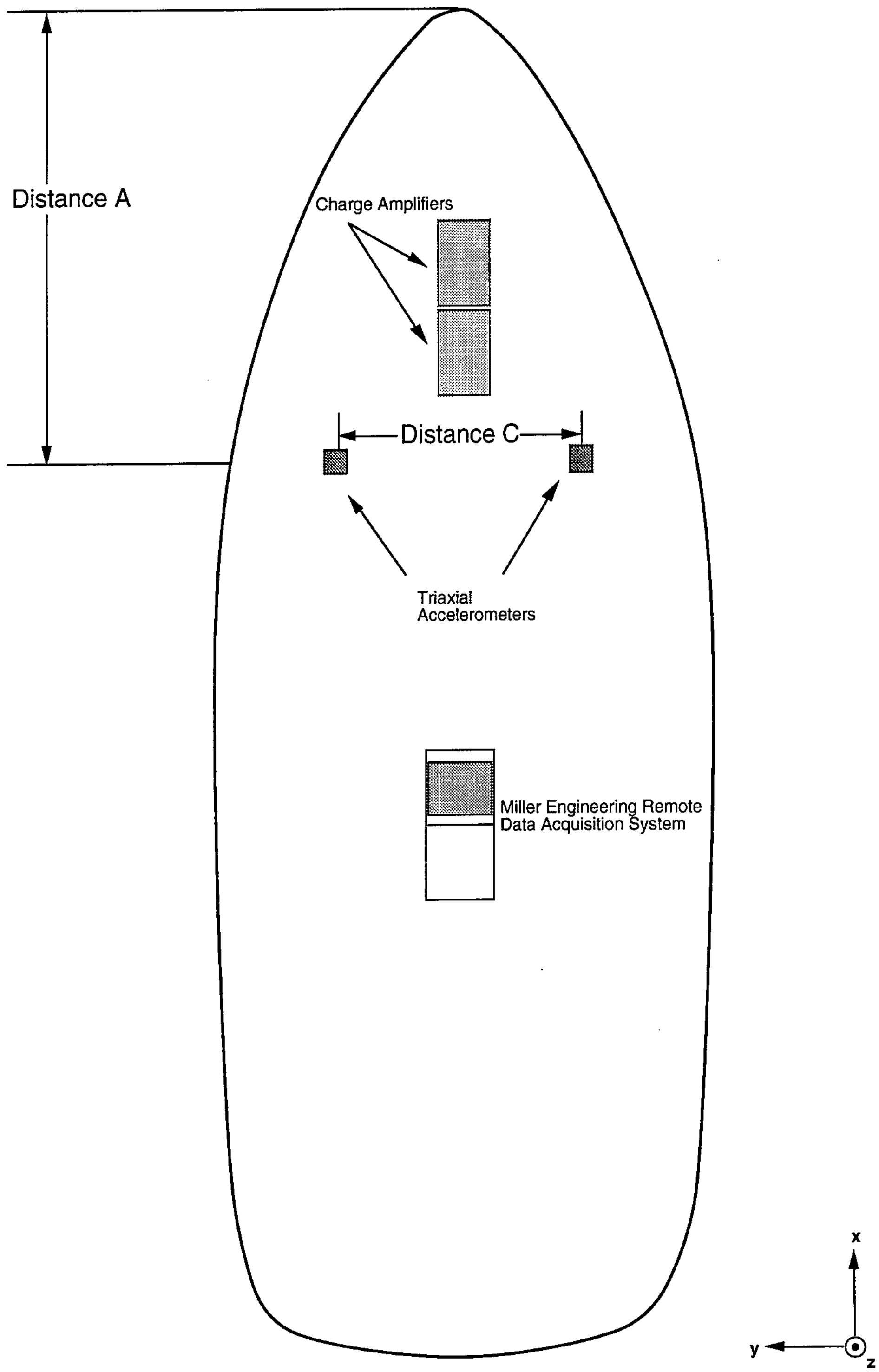


Figure B-1: Typical Equipment Layout Used in Test Boats

Appendix C

Test Procedure

The bow motions were to be measured directly with two triaxial accelerometers mounted in the bow seat positions: one port and one starboard.

Two different tests maneuvers were performed:

1) Hard turns
2) Wake crossings

Prior to the actual test runs, the boat speedometers were calibrated using a stopwatch to measure the time required to travel the known distance of 847 feet marked by an official American Water Ski Association slalom course.

The engines were trimmed in advance of the test run to those trim levels which would be appropriate for rigorous turning and cruising. Once set, the trim was held constant for each boat throughout the replications for that particular boat.

Hard Turns

The hard turn maneuver consisted of five hard turns to port and five hard turns to starboard. The maneuvers were conducted on relatively calm water at a speed of 40 mph. Once the speed of the boat reached 40 mph, the driver quickly cranked the wheel to the full turning position. After the apex of the turn, the driver straightened the wheel and prepared for the next turn.

Test Boat No. 2 could not attain 40 mph; consequently, the turns were conducted at its maximum loaded speed of 30 mph.

During each of these ten test runs, the Miller Engineering remote data acquisition system recorded triaxial accelerometer data. Upon remote triggering, the system was programmed to take 3600 scans at a rate of 600 scans per second for a total acquisition time of 6 seconds, which was ample to record the full turn maneuver.

Wake Crossings

A twin rig 25' center console boat was used as a wave generator. The engines were trimmed and run at a speed at which the maximum wake height could be generated. This maximum wave height was measured using the ultrasonic fluid level measuring device.

Three wake crossing maneuvers were tested per boat. The tests consisted of 40 mph wake crossings at three approach angles: 90, 60, and 30 degrees (Figure C-1). "Approach angle" is being defined here as the heading angle (the conventional naval architecture term for describing a ship's direction of forward motion with respect to the direction of wave propagation) minus 90 degrees. Each boat was equipped with a compass, which aided the drivers in achieving the heading angle that they were instructed to follow. The two boats always passed each other port to port. Table C-1 lists the five maneuver types including the hard turns.

During these test runs, the Miller Engineering remote data acquisition system recorded triaxial accelerometer data. Just before the initiation of a test run, the system was triggered to take six seconds of data. The Miller Engineering remote data acquisition system acquired 6000 scans at a rate of 1000 scans per second.

The wave heights generated by the wake generating boat were measured in a separate test. The boat was driven by a stationary pier from which the ultrasonic fluid level measuring device was extended. The water surface levels were sampled at 100 Hz during the four trials that were performed.

Total Data Gathering Runs (93 of 100)

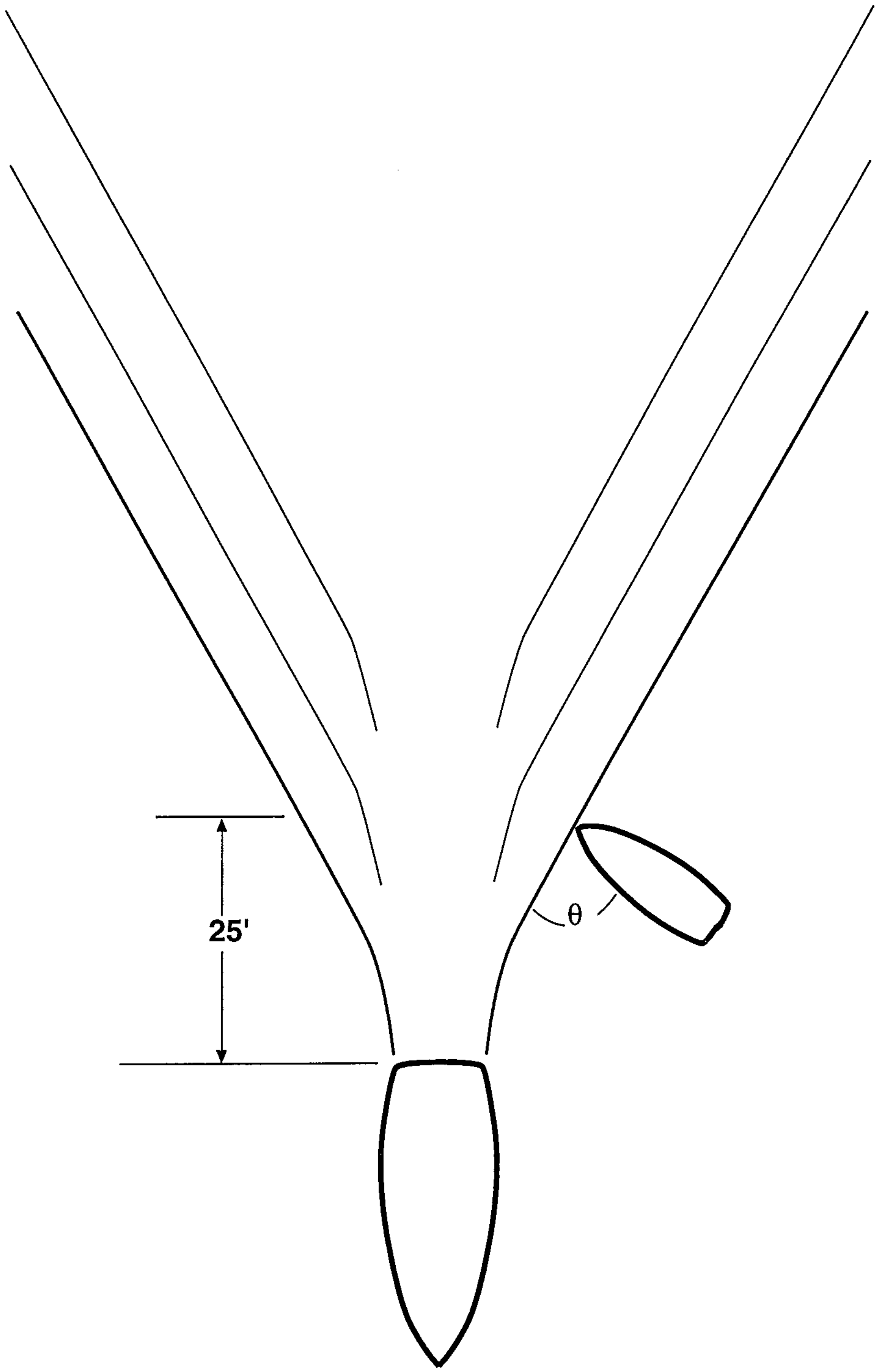
The total number of runs across all conditions, then, was four boats times five maneuvers times five replications equals one hundred runs. Of course in any massive data gathering effort such as this, all is not perfect. Consequently, there were approximately seven of the one hundred runs for which we did not consider the data reliable enough to include in the final analysis universe, leaving a balance of ninety-three full runs.

Table C-1: Test Maneuvers

Maneuver Number	Approach Angle	Boat Path	Speed (mph)*
1	180	Straight	40
2	150	Straight	40
3	120	Straight	40
4	N/A	Hard stbd. turn	40
5	N/A	Hard port turn	40

* Note: Test boat number 2 was tested at its top speed of 30 mph.

Figure C-1: Wake Crossing Diagram



Notes:
1) Drawing not to scale.
2) Wake approach angle = θ

Appendix D

Raw Data Analysis

The nearly one hundred data runs were then available, and still remain available, for any appropriate analyses to be done on them. After minor filtering to remove noise, a typical run of data appeared when charted out as Figure D-1, run FW5.E10 - A Hard Starboard Turn [also noted as Exhibit #3 in the Data Reduction Flow Chart (Figure D-2)]. This run was chosen for illustrative purposes because it represents about the most severe lateral (Y-Axis) acceleration condition found on any of our ninety-three runs of data.

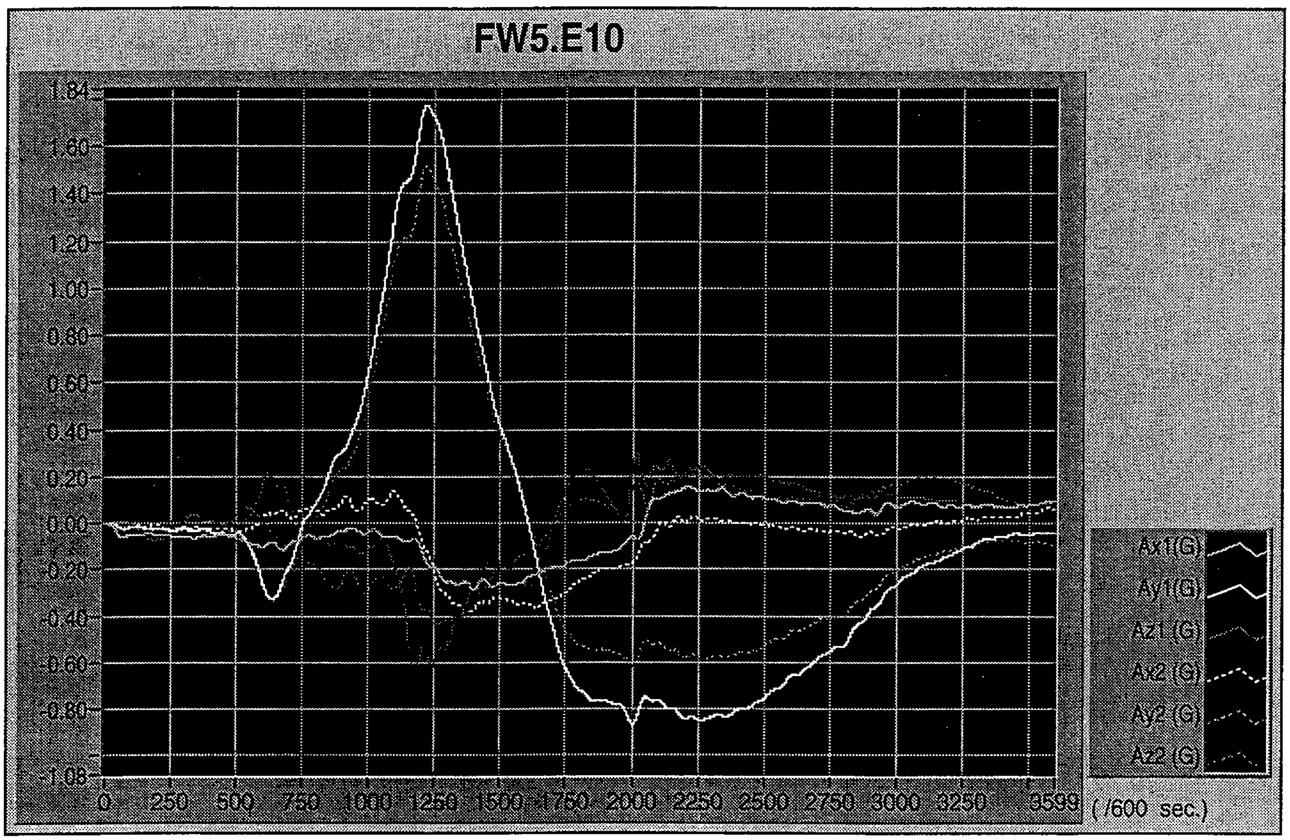


Figure D-1: Example Test Data: Hard Starboard Turn

Each step in the data reduction process beginning from the data acquisition and ending with the final illustrative display of the results is chronicled in the form of a Data Reduction Flow Chart (Figure D-2).

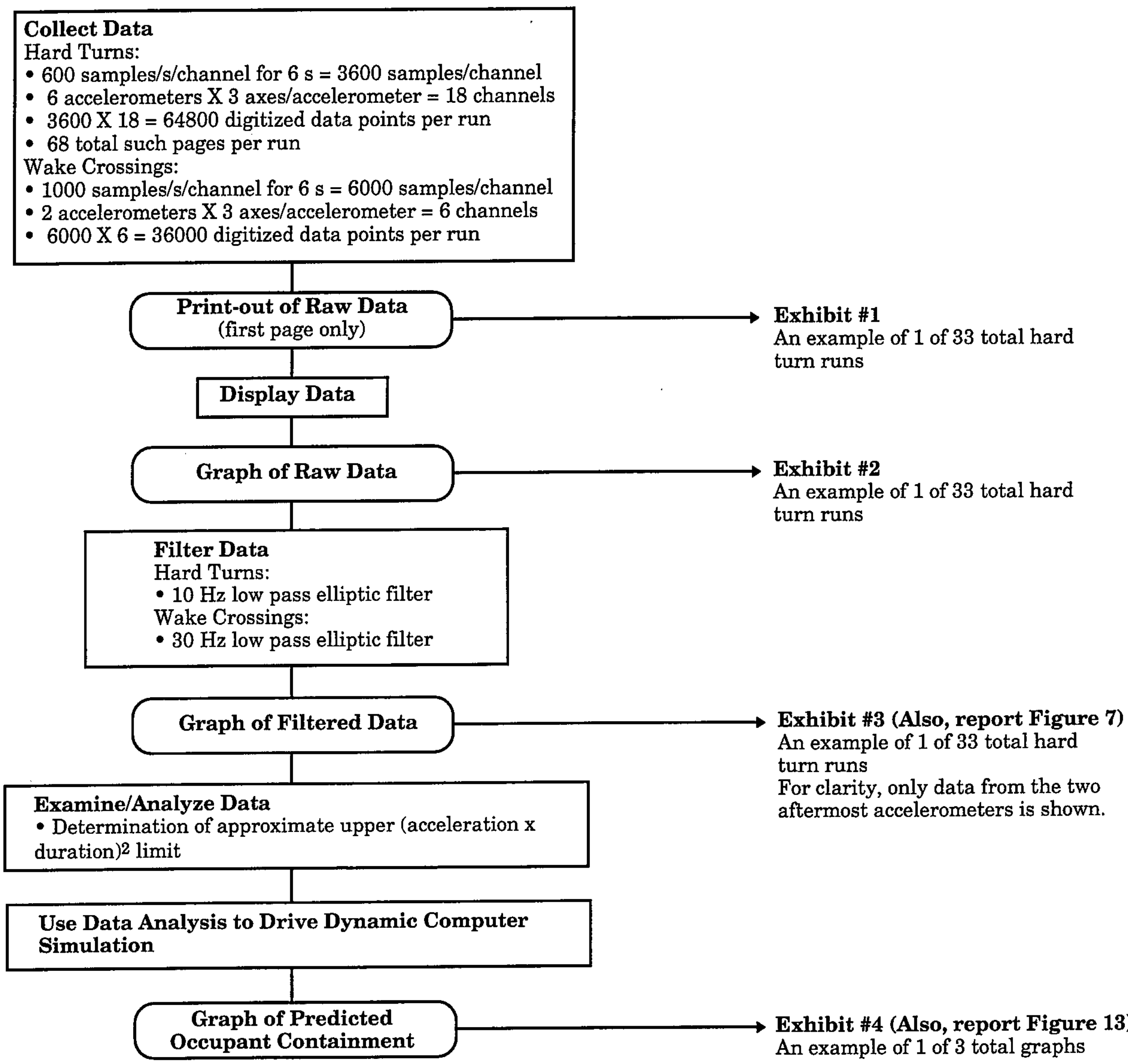


Figure D-2: Data Reduction Flow Chart

Appendix E

Description of Working Model® Dynamic Simulation Software

Within the software a multitude of variables are traced dynamically while being held under the constraints of the Laws of Motion. The driving external dynamic forces will ultimately cause the physical bodies within the model to move. In summary, Working Model®, then, solves mechanical motion problems, which are governed by differential equations arising from mechanical principles, using numerical methods. A problem is time-discretized so that Working Model® computes motion and forces, while making sure that all the constraints are satisfied. The mechanical principles can be expressed as simple equations such as the following:

$F = ma$
$a = dv/dt$
$v = ds/dt$
$\alpha = d\omega/dt$
$T = I\alpha$

Nomenclature:
a = acceleration
α = angular acceleration
$d\xi/dt$ = time derivative of ξ
F = force
I = moment of inertia
m = mass
T = torque
v = velocity
ω = angular velocity

The above equations are solved using numerical integration methods such as Euler, Predictor-corrector, and 4th-order Runge-Kutta. These methods involve approximating a problem by subdividing it into very small discrete time steps and incrementally computing the result at each time step. While this process is extremely tedious when attempted manually, today's computers can solve complicated problems using numerical integration in significantly lesser times.