Learning from a Tragic Capsize

Understanding How Excessive Loading Lead to a Capsize with Loss of Life Can Help Avoid Future Tragedies

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After sailing out to watch the fireworks on July 4th, 2012, on Long Island Sound, the 34-Foot Silverton, *Kandi One*, capsized with 27 people aboard. Tragically, three of the children aboard lost their lives. The general feeling among marine professionals was that that having so many people aboard a boat of this size was excessive and was the underlying cause of the capsize. It is important, however, to analyze the event systematically and see if hard numbers confirmed such gut feelings. At the request of *Soundings* magazine and using vital information from Eric Sorensen (and with valuable input and review from naval architects Eric Sponberg and Steve Dalzell), I set out to do just that.

A 1978-1988 model 34-foot Silverton

The *Kandi One* was a 1978-1988 model, a model long out of production. The builder is presently in Chapter 11, so we could not obtain hull lines and technical information from the manufacturer. Accordingly, to check the stability, a model of a near sister ship was created, duplicating the normal loaded displacement, overall dimensions, profile, arrangement, and configuration of the 34-foot Silverton of the 1978 to 1988 model years as closely as possible. You can see on the drawings that this analog model boat is very similar to the 34-foot Silverton.

The initial reviews, based on a mathematical and CAD analog model of the boat did not indicate a stability problem. This was contrary to expectations. Subsequently, Eric Sorensen, on July 20, 2012, conducted an informal inclining experiment on a sister ship of the 34 Silverton. The boat tested was the same model and configuration as the boat that capsized. The data from this inclining were analyzed to further investigate the GM and VCG. Though there were still unknowns and some issues, the inclining results were the most reliable data we had. Accordingly, the GM and VCG from the inclining experiment was used to reevaluate the stability of the boat.

The *Kandi One* raised after the capsize
Bill Bleyer photo, Twitter @BillBleyer

The inclining experiment indicated a VCG considerably higher than from the mathematical and CAD analog model. This quite high VCG is probably pessimistic, but—given the nature of the data available—is the closest to the actual boat.

The dimension and characteristics of the analog boat model, with the input for GM and VCG from the inclining

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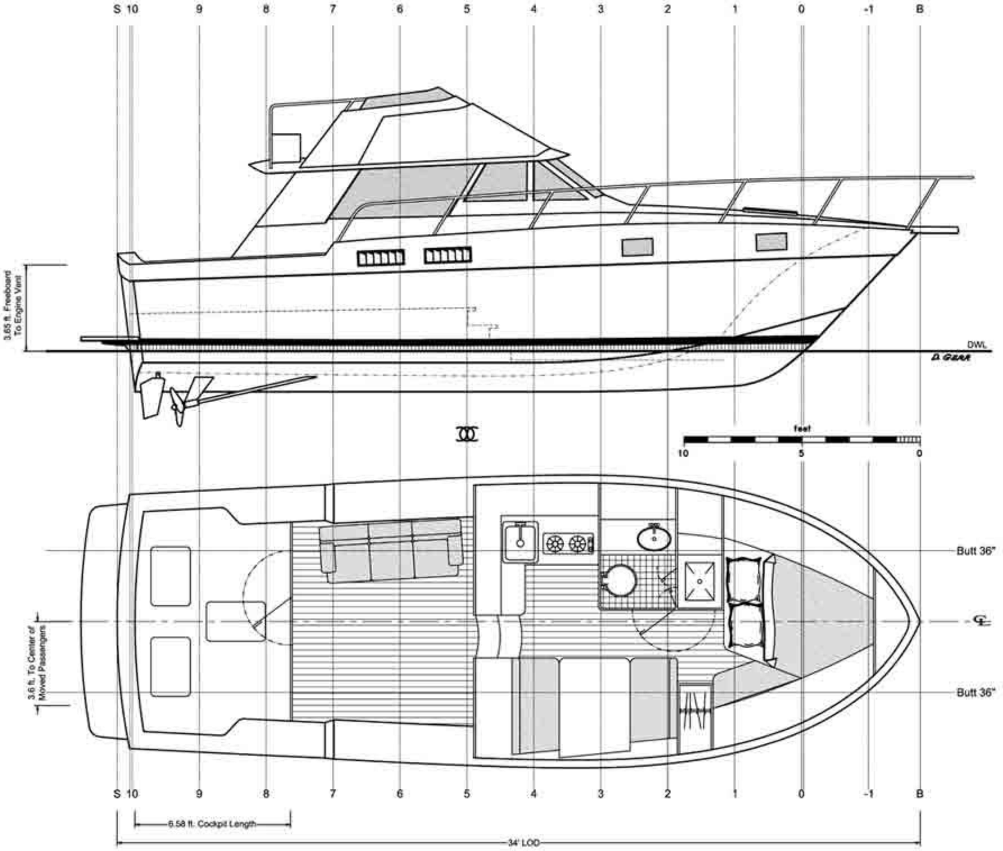
experiment, are in the normal load condition, which is assumed to be with full tanks and 4 crew:

LOA: 34.0 ft. (excluding bow pulpit and swim platform)
DWL: 28.56 ft.
Beam: 12.39 ft. (excluding rubrails)
BWL: 10.77 ft.
Fairbody draft: 1.72 ft.
Deadrise @ transom: 15 degrees
Disp.: 14,400 lb.
VCG: 3.88 ft. above DWL
VCB: 0.57 ft. below DWL
ITwp: 1,688 ft.^{4}
BM: 7.50 ft.
GM: 3.08 ft.
Waterplane area: 222.97 sq.ft.
Lb./in. immersion: 1,189 lb./in.

In the condition at capsize, with 27 people on board:
Disp: 17,640 lb.
DWL: 28.77 ft.
BWL: 10.98 ft.
VCG: 4.77 ft. above floatation waterline
VCB: 0.66 ft. below flotation waterline
ITwp: 1,746 ft.^{4}
BM: 6.33 ft.
GM: 1.17 ft.

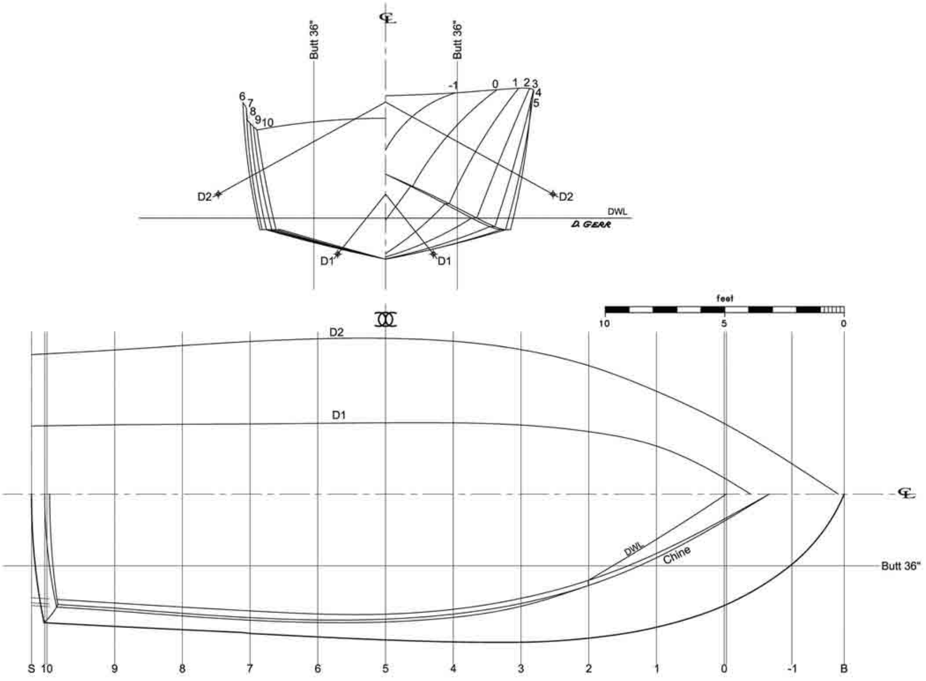


34 Ft. Express Cruiser - Similar to 34 Ft. Silverton

Evaluating Stability

In the U.S., there are currently no stability or capacity standards for pleasure boats over 26 feet long. (The one exception is for pontoon boats, which do have such a standard under ABYC.) So the question is how to evaluate the *Kandi One*'s stability in its condition at the time of capsize. The standard that we do have is the stability requirements for small commercial passenger vessels under the U.S. Code of Federal Regulations (CFR), Title 46, Shipping. 46 CFR has been used for decades to ensure the safety of passengers and has a solid record of success. It is also based on sound underlying naval-architecture principles. In addition, resulting heel angles and plot the curve of righting arms could be examined to get a clear picture of the stability characteristics of the heavily-loaded *Kandi One*.

46 CFR's stability standards for boats of this type, fundamentally deal with two criteria: passenger heel and wind heel.



Lines of 34 Ft. Express Cruiser - Similar to 34 Ft. Silverton

Learning from a Tragic Capsize continued

Passenger Heel

Working through 46 CFR for passenger heel:

The maximum allowable immersion for exposed waters is:

$$\text{Immersion} = \frac{f \times ((2 \times LOD) - (1.5 \times CL))}{4 \times LOD}$$

Where:
F = lowest or minimum freeboard, ft.
LOD = length on deck, ft.
cl = cockpit length, ft.

For this analog model it is:

$$\text{Immersion} = \frac{3.65\text{ ft.} \times ((2 \times 34\text{ ft.}) - (1.5 \times 6.68\text{ ft.}))}{4 \times 34\text{ ft.}} = 1.56\text{ ft.}$$

Plotting the heel angle at 14 degrees (next page) gives an immersion at 14 degrees of 1.29 ft. This is less than the maximum immersion allowable of 1.56 ft. so the governing factor is the maximum heel allowed which is 14 degrees.

The formula for required GM under 46 CFR is:

$$GM \geq \frac{N \times b}{18\text{ passenger / long ton} \times W \times \tan\theta}$$

Where:
GM = minimum required GM in feet
N = number of passengers
W = boat displacement in long tons
b = distance passengers move off centerline, ft.
θ = heel angle

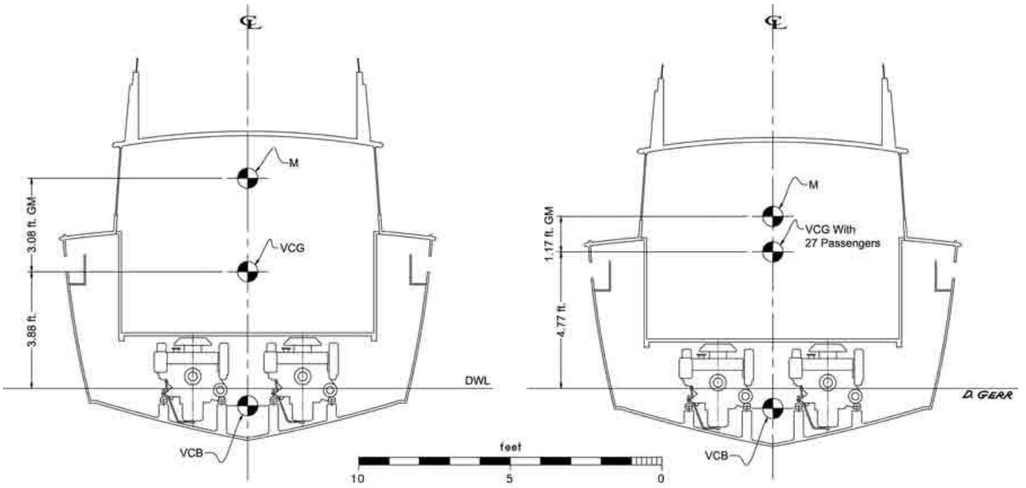
NOTE:
The “18 passengers/long ton” is a constant derived as: The weight of each passenger is 185 lb. 2/3rds of them moved to the side are then:

2/3 x 185 lb. = 123.95 lb., and 2,240 lb./long ton ÷ 123.95 = 18 passengers/long ton.

The requirements are for 2/3rds of the passengers shifted to one side of the vessel.

This works out as follows for the worst-case scenario with 27 adult passengers of 185 pounds each on board:

Maximum allowable heel angle is 14 degrees as found above.



At Normal Load - 4 Passengers
Full Tanks - 14,400 lb. Disp.

GM and VCG With 27 Passengers
Full Tanks - 17,640 lb.Disp.

GM and VCG at Different Loadings
Based on Sorensen Inclining

Displacement in this condition is 17,640 lb. or 7.88 long tons.

$$GM \geq \frac{27\text{ people} \times 3.6\text{ ft.}}{18\text{ passenger / long ton} \times 7.88\text{ tons} \times \tan(14^\circ)}$$

$$= 2.75\text{ ft. GM min.}$$

The GM of the boat, derived from the inclining experiment, as loaded in this condition is 1.17 ft. This less than half that required by the passenger-heel criteria under 46 CFR. The boat is not sufficiently stable with this many passengers onboard.

We can check this against the standard formula for heel with shifting weights. This formula is:

$$\text{Heel angle, degrees} = \arctan\left(\frac{W\text{ lb.} \times d\text{ ft.}}{\text{Disp. lb.} \times GM\text{ ft.}}\right)$$

Where:
W = weight moved, lb.
d = distance moved, ft.
Disp. = displacement, lb.
GM = metacentric height, ft.

Again for our analog model boat with 27 people aboard (all 185 lb.) and with the as-loaded GM of 2.87 ft., we get:

$$\arctan\left(\frac{4{,}994\text{ lb.} \times 3.6\text{ ft.}}{17{,}640\text{ lb. Disp.} \times 1.17\text{ ft. GM}}\right)$$

$$= 41\text{ degrees heel angle}$$

This not only exceeds the maximum allowable, but puts the boat past the downflood angle (next page). If all the passengers move to one side, the boat will capsize and sink.

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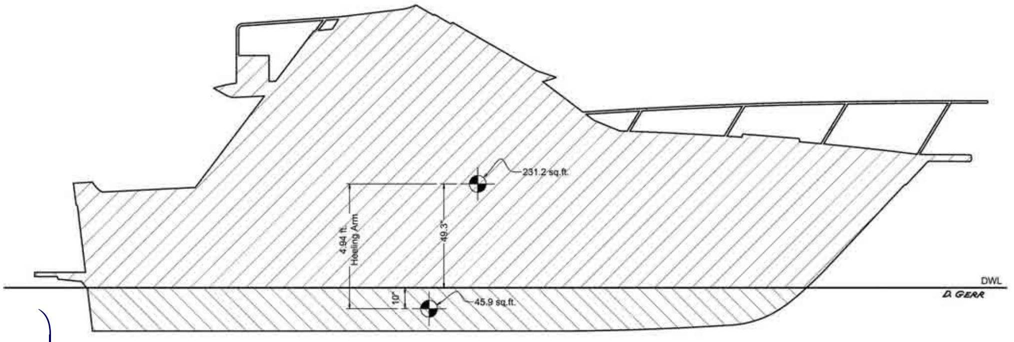
If we used 2/3rds if of passengers actual weight (adults and children) shifted to one side per the 46 CFR requirements, we get:

$$\arctan\left(\frac{3,347\text{ lb. x }3.6\text{ ft.}}{17,640\text{ lb. Disp. x }1.17\text{ ft. GM}}\right)$$

$= 30.9$ degrees heel angle

Though 30.9 degrees won't definitely capsize and sink the boat, this is too much heel as there is virtually no reserve margin of righting energy to the downflood angle. This is an unsafe condition. Any small wave or wind action would heel the boat over to the downflood angle, which would cause flooding and potential capsize.



Wind Heel Area and Arm

Wind Heel

Another consideration is wind heel criteria. The same maximum 14 degrees of heel applies. This can be checked as follows:

The 46 CFR criteria for wind heel is:

$$GM \geq \frac{P \text{ x } A \text{ x } b}{W \text{ x } Tan\theta}$$

Where:

GM = metacentric height, ft.

P = wind pressure in long tons per square foot, tons/ft.^{2}

P = 0.005 + (L ÷ 14,200)^2, tons/ft.^{2}
for ocean and coastwise service.

P = 0.0033 + (L ÷ 14,200)^2, tons/ft.^{2}
for partially protected waters such as lakes, bays, and harbors

P = 0.0025 + (L ÷ 14,200)^2, tons/ft.^{2}
for protected waters such as rivers and harbors

L = length between perpendiculars (waterline length for most ordinary boats), ft.

A = projected lateral area of boat profile above the waterline, sq.ft.

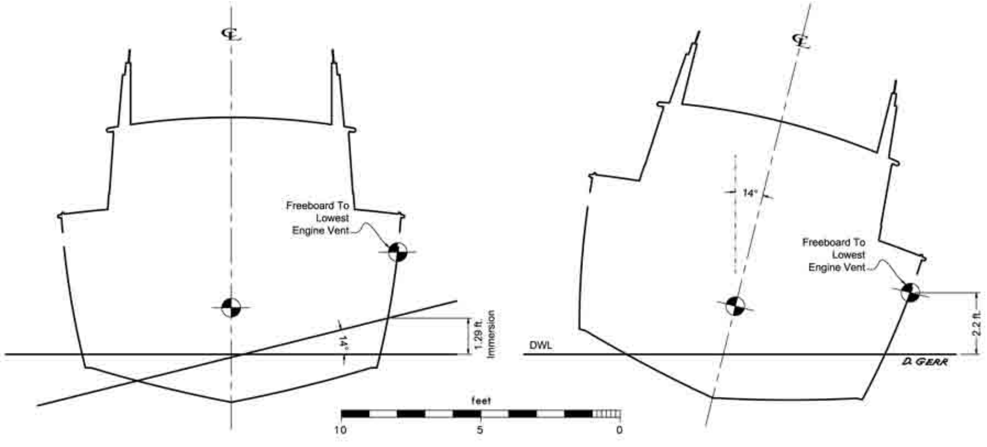
h = vertical distance from center of "A" down to center of underwater area (center of lateral plane), ft.

W = weight of vessel (displacement), long tons (tons of 2,240 lb.)

θ = heel angle = Heel not greater than between one-quarter to one-half of freeboard (as explained earlier regarding cockpit size), but never more than 14 degrees. The amount of heeled freeboard allowed is determined by the formula from CFR 178.330, exactly as described earlier.

The wind velocities in P for the factors 0.005, 0.0033, and 0.0025 are (using Martin's formula):
46 knots for ocean and coastwise
37 knots for partially protected waters
33 knots for protected waters

The "(L ÷ 14,200)2" factor in the wind-pressure calculation (P) is to increase the wind speed by 0.0458 knots for each foot of boat length.



Freeboard and Immersion at 14° Heel

Applying this to our analog boat in the 27-passenger load condition we get:

We can try 33 knots for protected waters—the least demanding criteria:

P = 0.0025 + (28.56 ft. WL ÷ 14,200)^2 = 0.002504 tons./ft.^{2}

Learning from a Tragic Capsize continued

$$GM \geq \frac{0.002504 \text{ x } 231.2 \text{ sq.ft. x } 4.92 \text{ ft.}}{7.88 \text{ tons x Tan}(14^\circ)} = 1.45 \text{ ft.}$$

The GM of the boat in this load condition is just 1.14 ft so the boat does not pass even the least rigorous condition for protected waters with regard to wind heel when loaded with 27 passengers.

We can check this against the standard formula for heel angle due to wind pressure. This is:

$$\text{Heel angle, degrees} = \frac{\text{P x 57.3 x Profile Area x Heeling Arm}}{\text{GM x Disp.}}$$

Where:
P = wind pressure for the selected wind speed, lb./sq.ft.
Profile Area = area of the profile of the boat above the waterline, sq.ft.
Heeling Arm = distance from the center of lateral plane of the underbody to the center of effort of the profile area, ft.
GM = metacentric height, ft.
Disp. = displacement, lb.

Use wind pressures (P) as follow for the intended boat use:
Ocean crossing (50 knots wind) = 13.2 lb./sq.ft.
Coastwise ocean (45 knots wind) = 10.7 lb./sq.ft.
Partially protected waters such as lakes, bays, and harbors (40 knots wind) = 8.5 lb./sq.ft.
Protected waters such as rivers, inland lakes, and sheltered harbors (35 knots wind) = 6.5 lb./sq.ft.
Note: For the U.S. Great Lakes, use coastwise ocean for summer service and ocean crossing for winter service.

For our analog boat in the 27-passenger-load condition and protected waters we get:

$$\frac{6.5 \text{ lb. / sq.ft. x } 57.3 \text{ x } 231.2 \text{ sq.ft. x } 4.95 \text{ ft.}}{1.17 \text{ ft. GM x } 17,640 \text{ lb. Disp.}}$$

$$= 20.6 \text{ degrees heel angle}$$

This is well over the 14-degree allowable heel and so not acceptable even for fully protected waters.

Stability Curve with Passenger Weights Shifted to One Side

Also shown is the curve of righting arms (next page) in the condition with two-thirds of passengers shifted the average maximum distance possible to one side of the boat. The total number of passengers, in the state when the capsize occurred, is 27. At 17 adults, 180 pounds each, and 10 children 90 pounds each, that's 3,960 pounds. Two thirds of that is 2,637 pounds. The maximum average distance the passengers can move to one side is 3.6 feet.

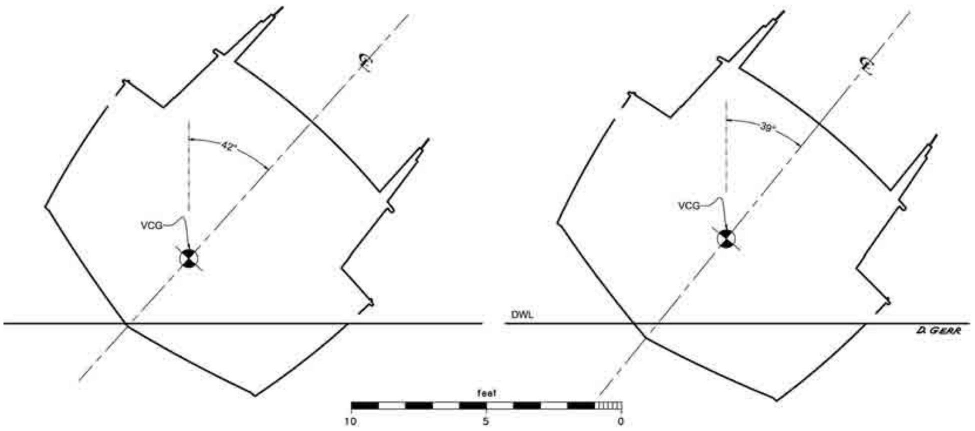
The resulting righting arm (GZ_1) at any angle of heel is found from:

$$GZ_1 = GZ - \left(\frac{w \text{ x } h}{W}\right)\cos\theta$$

Where:
GZ_1 = Righting arm with a weight shifted horizontally to one side, ft.
GZ = Righting arm without the weight shifted, ft.
w = Weight moved, lb.
h = Distance the weight is moved, ft.
W = Displacement/weight of boat, lb.
θ = Angle of heel, degrees

Applying this formula to the curve of righting arms with 27 passengers aboard (17,640 lb. disp.) gives the curve of righting arms with the two-thirds of passenger weight shifted. This is using 17,650 lb. displacement, 2,637 lb. shifted weight of passengers, and 3.6 ft. distance of weight moved.

You can see that in this condition (2/3rds of the 27 passengers shifted to one side) there is virtually no reserve stability left to the downflood angle. This is not acceptable and the boat is highly unsafe at this condition.

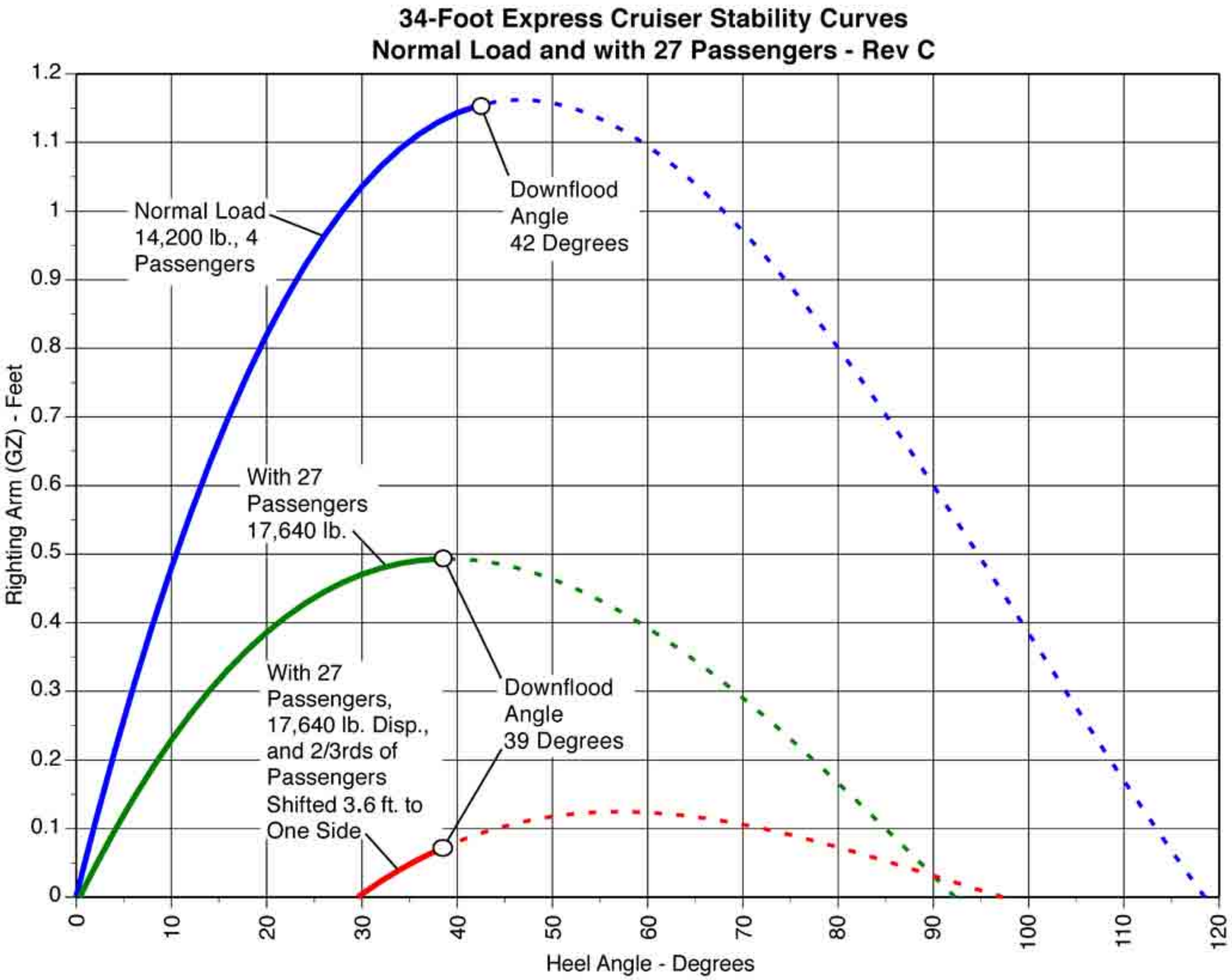


42° At Normal Load - 4 Passengers
Full Tanks - 14,400 lb. Disp.

39° With 27 Passengers
Full Tanks - 17,640 lb.Disp.

Downflood Angles

Learning from a Tragic Capsize continued



Conclusion
Using the GM and VCG derived from the inclining experiment added to the analog model of the boat, the results indicate that the 34-foot Silverton with 27 people aboard was dangerously unstable. The difference between the results from using the analog model only and from using the analog model with the VCG and GM from the inclining experiment are due to the much higher VCG and the lower GM from the inclining experiment. Though there are some questions about the high VCG indicated by the inclining—even if this is adjusted down somewhat—the boat would have highly questionable stability with 27 passengers aboard.

It is important to note that the 34 Silverton at normal or “standard” load, with 4 people aboard easily passes all the criteria above for stability for coastwise use under 46 CFR. For pleasure-craft use, the boat could safely carry 8 or 10 passengers in rough conditions coastwise and up to 16 or 18 passengers inshore in protected waters (as long as there weren’t an excessive number high up on the flybridge). The boat design itself is sound and safe. The load of 27 passengers (including, as reported, with 8 passengers high on the flybridge) was excessive and dangerous.