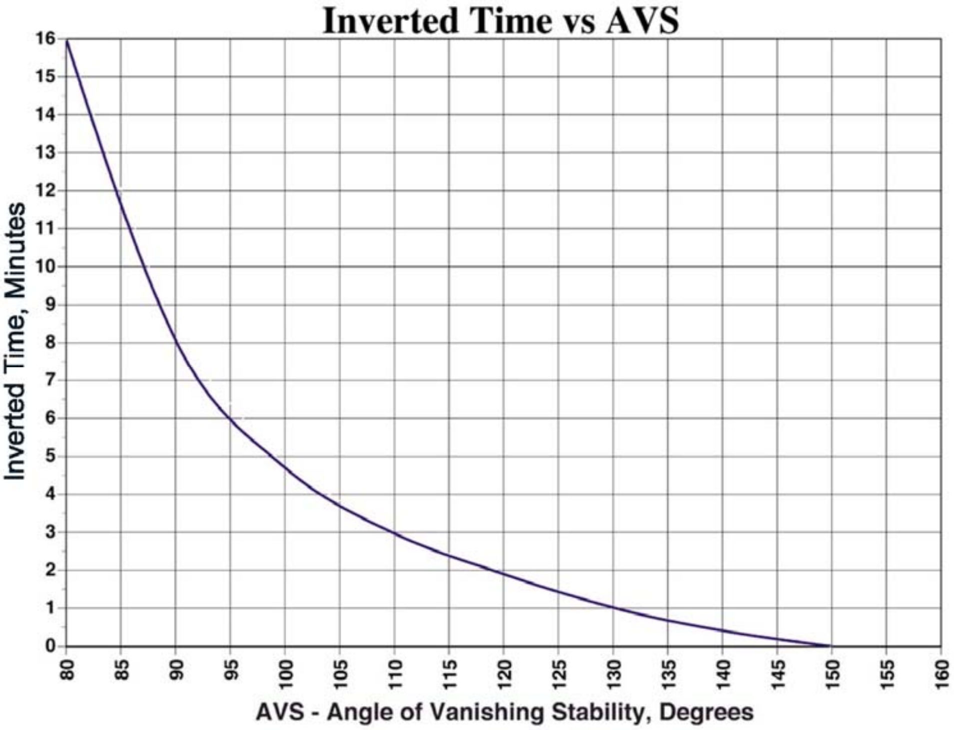
Stability Is The Key – Part 2

Understanding Stability and Sailboat Performance and Safety – Reserve Stability

By Dave Gerr, © 2007 Dave Gerr

In the previous article, we discussed initial stability or sail-carrying power—the stability that directly affects performance. Reserve stability is every bit as critical, but for safety. Reserve stability is measured in the number of degrees a boat can heel and still right itself. Any further heel, and the boat will—of it's own weight—continue on to capsize. The angle at which stability goes to zero is termed the angle of vanishing stability, AVS. It is also referred to as the "range of positive stability." If a boat maintains positive stability through up to 126 degrees, its AVS is 126 degrees.

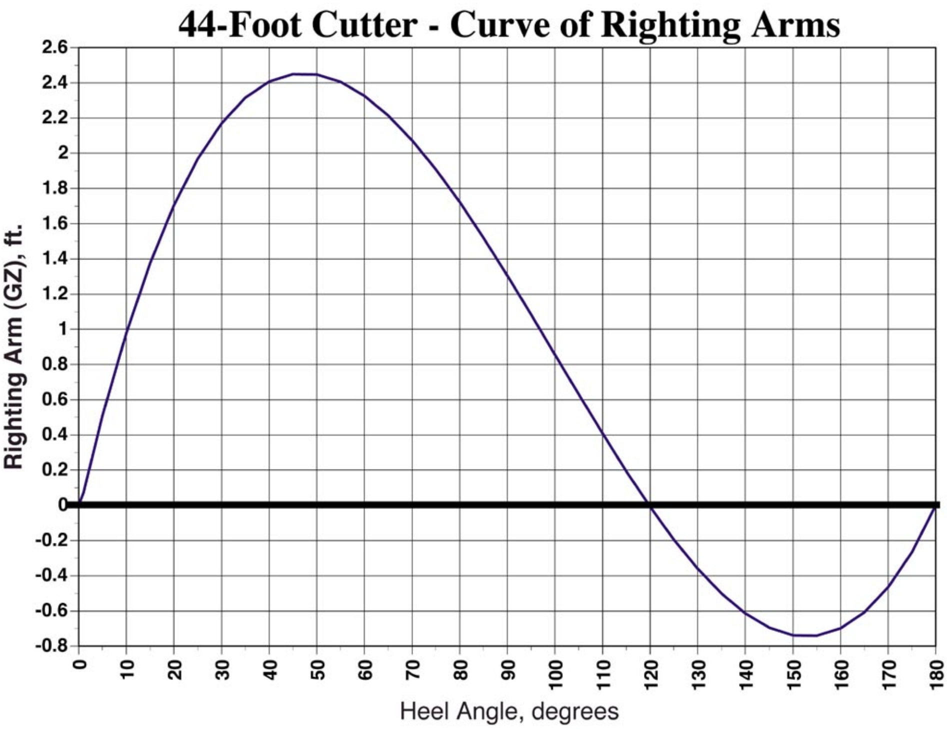
As a general rule, serious seaboats under 75 feet LOA should have a range of positive stability of 120 degrees or greater. Craft over 75 feet are acceptable with a range of 110 degrees. An analysis of boats in the 1979 Fastnet race—a race that had multiple vessels lost or damaged in a severe storm—produced an instructive curve. You can see that the greater the AVS the less time a boat will spend upside down before it self rights. With an AVS of 120 degrees or more, the inverted time will usually be 2 minutes or less. This is one of the drawbacks to wide, shallow-bodied hulls. Such hulls tend to have low AVSs, and worse still tend to be quite stable upside down. Indeed, one of the other aspects of reserve stability is the resistance of a boat to self-right once it has capsized. A moderate-beam hull, with a range of positive stability over 120 degrees, will only be slightly stable in the inverted condition. This means that virtually any sizable wave will roll the capsized hull over far enough for it to self right soon after. A wide hull, will be much more stable when inverted, and even a large wave may not roll it far enough to generate self righting.



Curve of Righting Arms

Reserve stability can be evaluated through a curve of righting arms (also called the stability curve), which plots the righting arm (GZ) against heel angle—see next page. As long as the GZ is positive, the boat will self right. At the angle the GZ turns negative, the boat will capsize. This shows immediately as the range of stability (AVS). The curve also shows other important things. The area under the positive portion of the righting arm curve represent the energy required to capsize the boat. The more energy required, the stronger the wind gust and the more sustained it must be to create a capsize. Alternately, the bigger and faster moving the wave must be to capsize the boat. Similarly, the area under the negative side of the curve represents the energy required to reright a boat once it's been capsized. Incidentally, the energy on these curves is measured in the rather odd unit of "degree feet."

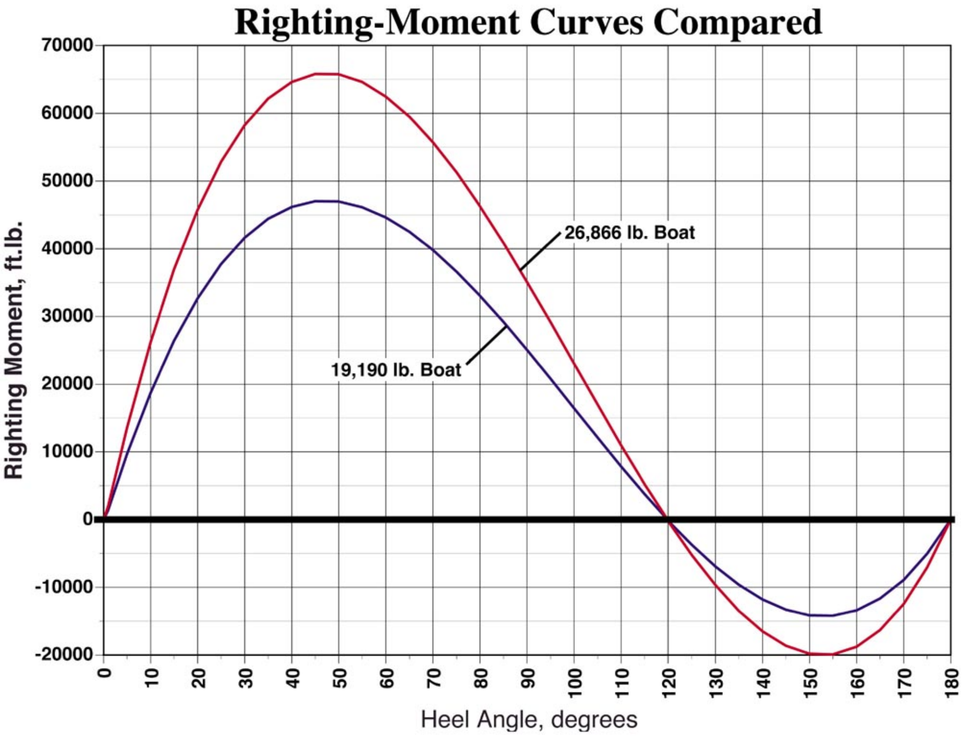
The same curve can be constructed using the righting moment (RM)—see next page. Remember, RM is just GZ times displacement. The curve will look the same whether it's plotted as RM or GZ, but—you should use RM when plotting different boats on the same scale for comparison. This will immediately show the difference between boats with the same GZ but differing displacement. You can see, on the Righting-Moment Curves Compared graph, that the area under the stability curve is much larger for the heavier 26,866-pound boat that for the 19,190-pound boat, even though both have the same GZs at all angles of heel. This means that it requires more energy to capsize the larger, heavier boat. This is the reason that bigger boats are inherently safer (broadly speaking) offshore. The energy on righting-moment stability curves is measured in “degree foot-pounds.”



Estimating AVS

The exact way to determine AVS is by doing a detailed weight study to find VCG and then a computer analysis to determine GZ at every angle of heel based on the precise hull form. You can also manually analyze each angle of heel, at 10-degree intervals (the old way) using Skene’s method. This works well too, but is quite labor intensive. Whichever method employed, it not only requires a lot of time and work, but a full set of drawings for the boat.

The Wolfson Unit of Southampton University developed a formula for estimating AVS for contemporary keel sailboats of ordinary form and proportions. Centerboarders, and keel centerboarders are not accurately handled by this formula which can’t give an AVS less than 110 degrees. For standard keel boats; however, the Wolfson formula will allow you to estimate the AVS of a boat. Keep in mind, however, that this is just an estimate, though a fairly reasonable one. It is excellent for preliminary design or investigating an existing boat you have limited data on.



You need to know the following:

Hull draft (also called “draft canoe-body,” or DCB), feet
Ballast, pounds
Displacement, pounds
Beam overall, feet
Density of seawater = 64 lb./cu.ft.
Density of freshwater = 62.4 lb.cu.ft.

Hull draft or canoe-body draft (DCB) is the draft without the keel. For this formula, it’s taken at the midships section of the boat by drawing a vertical line one-eighth of total beam out from the centerline, and measuring down from the waterline to where this line intersects with the hull bottom. If you don’t have a midships section, measure the DCB on the profile view of the boat at the centerline, and subtract 10%.

Say our boat had the following:

DCB = 1.89 ft.
Ballast = 7,484 lb.
Displacement = 19,190 lb.
Beam overall = 11.66 ft.

First, find the ballast ratio:
BR = 7,484 lb. ÷ 19,190 lb. = 0.39

Next find the displacement in cubic feet (for seawater in this case):
19,190 lb. ÷ 64 lb./cu.ft. = 299.8 cu.ft.

Now, find SV:

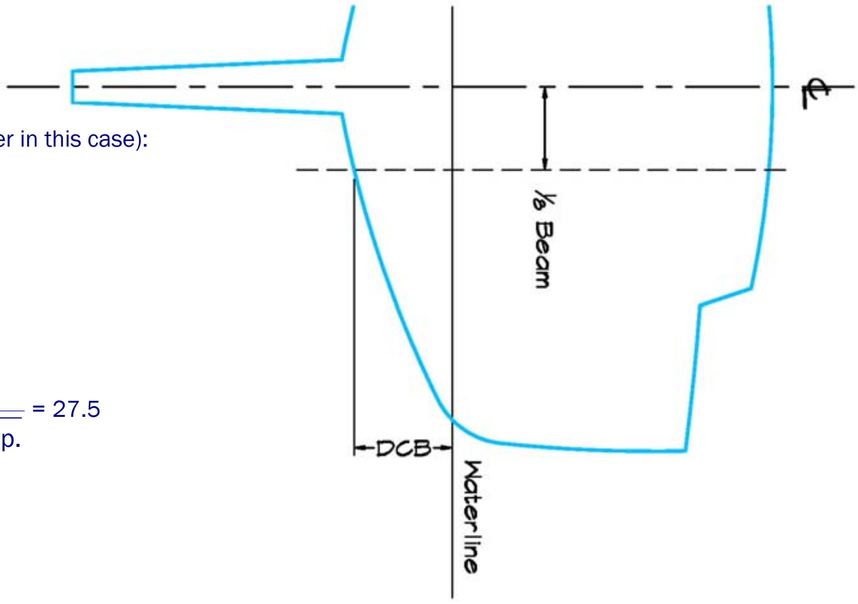
$$SV = \frac{\text{Beam}^2}{\text{BR x DCB x} \sqrt[3]{\text{Disp., cu.ft.}}}$$

$$SV = \frac{(11.66\ \text{ft. Beam})^2}{0.39\ \text{BR x}\ 1.89\ \text{ft. DCB x} \sqrt[3]{299.8\ \text{cu.ft. Disp.}}} = 27.5$$

Next, find the estimated AVS

$$AVS = 100 + \frac{400}{(SV - 10)}$$

$$AVS = 100 + \frac{400}{(27.5\ SV - 10)} = 123\ \text{degrees}$$



Finally, I make an adjustment to reduce the standard Wolfson-method AVS, as I've found it seems to slightly overestimate AVS. So multiply the AVS by 0.97.

$123° \text{ x } 0.97 = 119.3°$ AVS estimated

This is very close to 120 degrees, so this boat would just barely meet the criteria for offshore cruising. The curve of righting arms, or stability curve for our 44-foot cutter shows this clearly. (This is the boat pictured and discussed in the first part of this article, in the previous article.)

Increased Freeboard: Increased AVS

One of the things that the Wolfson estimate does not take into account is that increased freeboard increases AVS. At large angles of heel, higher freeboard shifts the heeled center of buoyancy further away from the center of gravity than lower freeboard. Not only does this increase AVS, but it also increases the downflood angle.

On shoal-draft boats—even boats so shallow they have no external keel—AVSs of 120 degrees can be achieved by: keeping the hull structure light; ensuring the ballast ratio is above 35 percent (sometimes with all inside ballast); and increasing freeboard. Properly proportioned and designed, such shoal centerboarders and keel-centerboarders have proven themselves as excellent seaboats.

Added Weights Reduce AVS

It is easy to add weights and weights are almost always added above the waterline. Accordingly, these weights raise the VCG (vertical center of gravity) and reduce both initial and reserve stability. If our example boat above were overloaded, its displacement would increase and its ballast-ratio decrease, and AVS would then be lower than 120 degrees.

Adding weights up high on the mast is even more critical. Adding a radar unit, and masthead light and instrument package, could reduce AVS by a full degree or more.

Even more critical are heavy masts. There is a tendency for offshore voyagers to simply beef up the mast and rigging. Increasing the weight of the mast and rigging may make them more rugged, but this also reduces the AVS. It's a delicate balance and needs careful thought. In-the-boom, roller-furling masts must be significantly heavier than standard masts, because the top-to-bottom slot in the mast weakens the section. The mast accordingly must be beefier to compensate. In addition, there's the added weight of the roller gear. Switching from a well-proportioned, tapered standard mast to a common, untapered, in-boom-furler mast can reduce the AVS by 15 degrees, sometimes more! This too needs careful consideration.

The Safe Energy Ratio

For offshore work, the area under the negative side of the stability curve must be less than one-third the area under the positive side. This makes it very likely that any sea conditions that were severe enough to capsize a boat in the first place, will also be severe enough to reright that boat quickly.

The area under the curves can be estimated by the following:

Positive energy (area) = AVS x Max. GZ x 0.63
Negative energy (area) = (180 - AVS) x Min. GZ x 0.66

Looking at the curve of righting arms you can see that the maximum positive GZ is 2.45 feet, and the maximum negative GZ is -0.74 feet.

Positive energy = 119.8 x 2.45 ft. Max. GZ x 0.63 = 184.9 degree feet
Negative energy = (180 - 119.8) x 0.74 ft. Min. GZ x 0.66 = 29.4 degree feet

29.4 degree feet ÷ 184.9 degree feet = 16%

This is well under the minimum one-third area and so quite suitable for offshore work.

Downflood Angle

Naturally, things aren't quite as simple as all this and the standard stability curves assume that the boat is all sealed up like a submarine. The reality is that, once most boats are heeled over more than 110 degrees, water will start to enter the boat through ventilators and small leaks at hatches and windows. Any such leaks reduce stability by flooding the boat with water on the down side (shifting ballast on the wrong side). Worse still, such water sloshes about, and the sloshing action (known as "free-surface effect") further reduces righting moment. Still—if all the hatches and windows are buttoned up tight and ventilators are off the side decks and well protected with water-trap boxes—this effect Is minimal.

Full stability analysis, however, assumes that any principle hatch—usually the companion hatch or hatches—might be left open. Every so often, freak wind gusts or freak waves have rolled boats over very quickly without warning in otherwise moderate weather. A boat could have an AVS of 130 degrees, but a downflood angle of 112 degrees. If the hatch were open water could flood the boat long before the theoretical 130-degree AVS and the boat might capsize and sink.

Generally, the downflood angle should be over 110 degrees for offshore boats. As a rule—with the companion hatch on the centerline—this is almost automatic. You'd be surprised; however, how much reduction in the downflood angle can result from companion hatches off centerline. A hatch all the way to the side of a standard trunk cabin could reduce the downflood angle by 20 degrees or so! Two nearly identical models of the same boat—one with a centerline hatch and the other with hatch off to the side—could have downflood angles of, say, 122 degrees and 104 degrees respectively.

Capsize Screening Number

Both wind or wave action can capsize a boat and—as we've seen—the energy required increases with larger heavier boats. In fact, a boat that is relatively heavier for a given beam has a greater resistance to capsize than a boat with wider shallower hull at the same displacement. (Remember, the wide shallow hulls which increase sail-carrying power reduce reserve stability characteristics.)

The capsize screening number evaluates this aspect of reserve stability. It is simply:

$$\text{Capsize Number} = \frac{\text{BOA}}{\sqrt[3]{\text{Disp.}}}$$

Where:
BOA = beam overall, feet
Disp. = displacement in cubic feet

The lower the capsize number the more resistant the boat is to sudden-energy capsize events. Any capsize number under 2.0 is acceptable for offshore work. If you're planing to round the Horn or cruise Antarctica, a capsize number of 1.7 or less is indicated; but for ordinary voyaging cruisers such a low capsize number is more than required.

Our example 44-foot cutter has a displacement of 19,190 pounds (299.8 cu.ft. saltwater) and a beam overall of 12.25 feet, so:

$$\text{Capsize Number} = \frac{11.66\ \text{ft. BOA}}{\sqrt[3]{299.8\ \text{cu.ft. Disp.}}} = 1.74$$

This is well under 2, and so indicates good resistance to capsize.

Another use for this number is to modify the required minimum AVS. For ordinary ocean cruising, a capsize number of 1.7 or less, will give acceptable safety with an AVS of 115 degrees, rather than 120 for boats under 75 feet LOA. For boats over 75 feet, it allows an AVS of 105 degrees.

Keep in mind; however, that the capsize screening number doesn't mean much by itself. It must be used in conjunction with other characteristics discussed above when evaluating reserve stability.

Evaluating Reserve Stability

Reserve stability is frequently talked about in terms of AVS and nothing else. This is too simple an approach. Vessels that are doing serious offshore work need to meet several criteria to ensure the best resistance to capsize:

1) For boats under 75 feet LOA, AVS to be 120 degrees or higher, unless the capsize number is 1.7 or less, in which case 115 degrees or higher. For boats over 75 feet, AVS of 110 degrees or higher, unless the capsize number is 1.7 or less, in which case 105 degrees or higher.

2) The area under the negative side of the stability curve should be less than one-third of the area under the positive side.

3) The downflood angle should be 110 degrees or greater.

4) The capsize number should be less than 2.0 for serious ocean cruising, and 1.7 or less for extreme ocean voyaging (or for reduced AVS, as above).

5) The Dellenbaugh angle should be within the range shown on the chart (see previous article) for the length of the boat. This ensures that the initial stability is properly matched to the rig.

A boat that meets all these criteria has stability characteristics that indicate it is suitable for serious offshore voyaging with regard to stability.

STIX — The Capsize-Screening Number

A somewhat recent development in evaluating stability is that boats built for sale in Europe or an EU country must be built to ISO standards to obtain their CE mark. Without this mark, indicating compliance with the applicable ISO standards, no boat can legally be sold or operated in EU waters if they have an EU-country flag. (U.S. boats can sail EU waters, under the U.S. flag, without the CE mark.)

One of the very many individual ISO standards governs sailboat stability. Like most ISO documents, this standard quite convoluted. Rather than simply applying the fundamentals described above, the ISO stability standard calculates numerous separate values and adds them together in prescribed ways to get a stability index number known as the "ISO stability index number" or STIX (**ST**ability Inde**X**).

Because complying with STIX under ISO is now the law in Europe, there is a tendency to interpret STIX as a good indicator of seaworthy stability in the U.S. I personally don't believe that STIX is all that reliable an indicator. Nevertheless, the STIX number is a reasonable marker, but is not as reliable—in my opinion—as simply applying the basic concepts above (along with one or two others involving dynamic stability—too complex to go into here—for really accurate results by designers).

Another peculiarity of ISO CE is that—rather than using the perfectly good Beaufort sea-state scale—it developed it's own set of sea-state categories. (Why reinvent the wheel?) In any case, ISO sea-state categories range from A through D, with A being extreme ocean storms and D being pretty close to calm. A boat intended for offshore work should have a category A or B STIX number. The current regulation-required STIX numbers for each category are as follows:

Category	Min. STIX No.
A	32
B	23
C	14
D	5

Category A is truly extreme weather. It is defined as significant wave heights of 23 feet and maximum wave heights of 46 feet. Most sailors—even ocean-crossing ones—will go their entire lives without seeing such conditions. Category B is more than adequate for most average cruisers, with significant wave heights at 13 feet, and maximum heights at 26 feet.

Regardless, category A is the holy grail of ISO CE for ocean-going sailboats. If you are looking at a European-built boat with CE category A, you're more than likely looking at a safe seaboat. I'm not convinced that a STIX of 32 (and the many other requirements for category A) actually ensure that the boat is any safer than a well-built U.S. sailboat intended for ocean cruising and without a CE mark. In fact—having run through ISO CE and STIX for a design recently—I'm not convinced that any of this is the best approach for evaluating or making safe boats. That; however, would be the subject for another article.

If you want to learn more about the STIX number refer to an article by Rolf Eliasson, in issue 81 (Feb/Mar. 2003) of *Professional Boatbuilder* magazine, starting on page 128.

60-foot BOC racer *Holger Danske*, designed by Dave Gerr

Photo: Onne van der Wal

> *"If one is always to be overawed by the circumstances which may arise against one—no full-rigged ships would never have been built."*
>
> . . . Allan Villiers