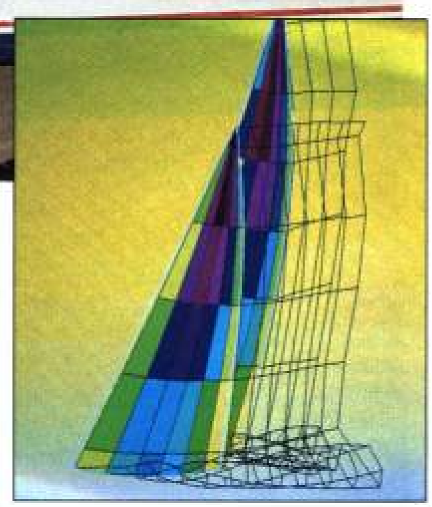
Fluid Dynamics

How Modern Science and Sailing Discovered Each Other

The foundations of sailing have been demolished, quietly and completely. No one saw it coming, and very few understood it when it happened. In fact, most of us are unaware of it even now. But today, some of those who swung that muffled wrecking ball are the leading architects in the reconstruction of our relationship with wind and wave. By Doug Logan



computer art courtesy of North Sails, Inc.

There were more than a few experienced mariners who suspected the earth wasn't flat before Columbus out-and-out said so, just as there were farmers and druids who had a hunch that the earth revolved around the sun long before people like Copernicus and Galileo declared it. In those days people tended to keep such thoughts to themselves, lest they be forced to take poison or refrain from talking for the rest of their lives. But in the early 1970s, when Arvel Gentry debunked the popular explanations of what made sailboats go (in a series of articles in *Sail* magazine); when he explained that concepts like the "slot effect" and the "venturi effect" were seriously flawed and simply didn't have much to do with the true dynamics of air through a sailplan, he was, by and large, ignored.

The slight stir Gentry created faded quickly. As recently as 1990, in these very pages, we could see sailors and engineers trying vehemently to deny what had been obvious textbook stuff to people like Gentry and A.M.O. Smith and C.A. Marchaj for decades. Gentry and company were weighing in with talk of stagnation streamlines, separation bubbles, starting vortices, Kutta Conditions. They were saying outright that much of what modern sailors had been taught about lift and drag on an airfoil was just rot. And they weren't appreciated. Even six years ago, real aerodynamics still did not, as the computer used to say, compute — even for many at the top levels of the sport.

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– Arvel Gentry

Well, now they do compute. Today, no serious naval architect or sailmaker isn't well aware of the scientific basics championed by Gentry and his colleagues — how airfoils develop lift from both linear flows and circulation flows, how sails fly or don't fly together, how hulls and their appendages slip through the water. There are few in the industry who work without the help of computer programs that model and calculate the effectiveness of shapes passing through fluids, that make quick work of reckoning the numbers inside concepts that have long been unapproachable by most sailors, and that, most importantly, can portray the quantified data graphically in moving, three-dimensional, full-color images. All of a sudden the real science seems a lot less daunting.

The essential challenge, of course, is in trying to make a vessel move nicely through two fluids simultaneously, part of it stuck down into thick, slow-moving water, and the other part stuck up into thin, fast-moving air. Add peripheral challenges like waves, local wind dynamics, geographical effects on both fluids, and the limitations of boat design, and you've got an excellent puzzle to solve. This is at least partially what has drawn in the scientists from the aerospace industry and elsewhere. The scientists, in turn, have proven themselves to the sailors, if not always in theoretical terms, certainly in terms of their ability to produce one magnificent thing, a thing that has often taken seat-of-the-pants sailors lacking an intimate understanding of fluid dynamics a generation or two to achieve: a fraction of a knot. So today, at the top levels of the sport, and particularly in the America's Cup, the scientists are very much in demand.

Advancement at the cutting edge of sailing science is fast, bumpy and nerve-wracking. There's still plenty of confusion about what computers can and can't do in this sport. So it's a good time to go back and have a look at the origins of the almost invisible watershed that has occurred, and to check in with a few of the people responsible for it then and now.

Heretics

Gentry, now a Technical Fellow of the Boeing Company, got his masters degree in Aeronautical Engineering from USC in 1958, and proceeded to work at Douglas Aircraft for 19 years, the last 10 years in the Aeronautical Research Group. He then moved to Seattle, and has worked at Boeing ever since, mostly in the Aerodynamics Research Department, where he has been concentrating on computational fluid dynamics. A primary purpose of CFD is to provide estimations for the lift and drag of a vessel's various surfaces by passing them through an imaginary fluid and calculating the pressures involved in multiple locations. In boat design, the resultant CFD codes can be fed into Velocity Prediction Programs, the theoretical performance numbers for a boat operating in a full range of wind angles and windspeeds. By now, VPPs in the form of polar diagrams are familiar to the great majority of big-boat racing sailors. In the 1960s, however, when Gentry was pondering his shake-up of the sailing status quo, all these numbers were barely a gleam in the computer's eye.

"I got involved in the technical aspect of sailing because I started racing," says Gentry. "Engineers learn an awful lot first by reading everything we can get hold of, to find out what the state of the art is. As I started to read, I began to realize that most of what was written about the aerodynamics of sails was wrong, or certainly very misleading. That's what launched me on a quest — call it what you want — to try to gather information as to how sails work."

Gentry began experimenting on his own Cal 20. He set up a telescoping pole with a tube and a compressor that blew a stream of soap bubbles out in front of his sailplan so that he could see where the air flowed. To refine his view of the whole flow pattern he put 500 short tufts in rows on his sails, starting right at the luff: "People sailed by and thought I was crazy. At the time, I was doing some research on what's called the laminar separation bubble, trying to correlate when the bubble formed on a thin airfoil, asking when the angle of attack is increased, when does this bubble burst and the whole airfoil stall? This correlation began to show that the thinner the airfoil, the more pronounced the separation bubble and the quicker it forms. And that immediately told me that the ultimate thin airfoil is the sail. As soon as I saw that, I realized that the reason why people put their telltale in a window so far back on the sail is because if they put it closer to the luff on the lee side of the sail, the telltale would flutter, but the boat would still be going great. They didn't understand that there was this separation bubble that would form, and then reattach, and then go smooth on them again."

On most boats the habit of installing telltales a foot or so back from the luff persists. From a practical viewpoint it may not make a big difference to have telltales so near the luff that they're nearly always stalled going upwind, but it's important to realize that they're not stalled because they're blanketed: "It's the pure fact that the stagnation streamline is in a little bit on the windward side of the sail rather than right at the leading edge," says Gentry. "Then the flow has to make this sharp turn around that corner to get around on the lee side. The flow separates off, goes a few inches back, and then reattaches."

Gentry had his evidence lined up when he caused his stir, but the refusal of so many back then to accept the evidence and learn the lesson was only partly baffling to him: "As I've said before, aerodynamics is not necessarily an intuitive science. You can't just sit there and stare at your navel and come up with conclusions. There are some rather strange things that happen, and they're sometimes very hard to explain. Certainly the authors of the old books and papers on aerodynamics — I'm talking about things that came out in the 1920s and '30s — didn't have the computers we have now to be able to understand things. They drew conclusions that unfortunately turned out to be wrong — like the slot effect between a slat on a wing and the leading edge of the wing, and the idea that there's a venturi somehow in there, and that this high-speed flow in there is somehow 'energizing' the boundary layer — without ever stopping and thinking about what these terms meant. What does 'energizing' mean? What would it do if you had high-speed flow in there? It sounds OK, but they didn't have the tools to do the analysis. These things carried over into the sailing literature. People started talking about a simple thing like how an airfoil gets lift: 'Gee, the air has to speed up over the top to reach the trailing edge at the same time as the flow over the bottom.' That was before we had the ability to calculate all these flows and show that the air that flows over the top of the airfoil gets to the trailing edge long before the flow on the bottom does."

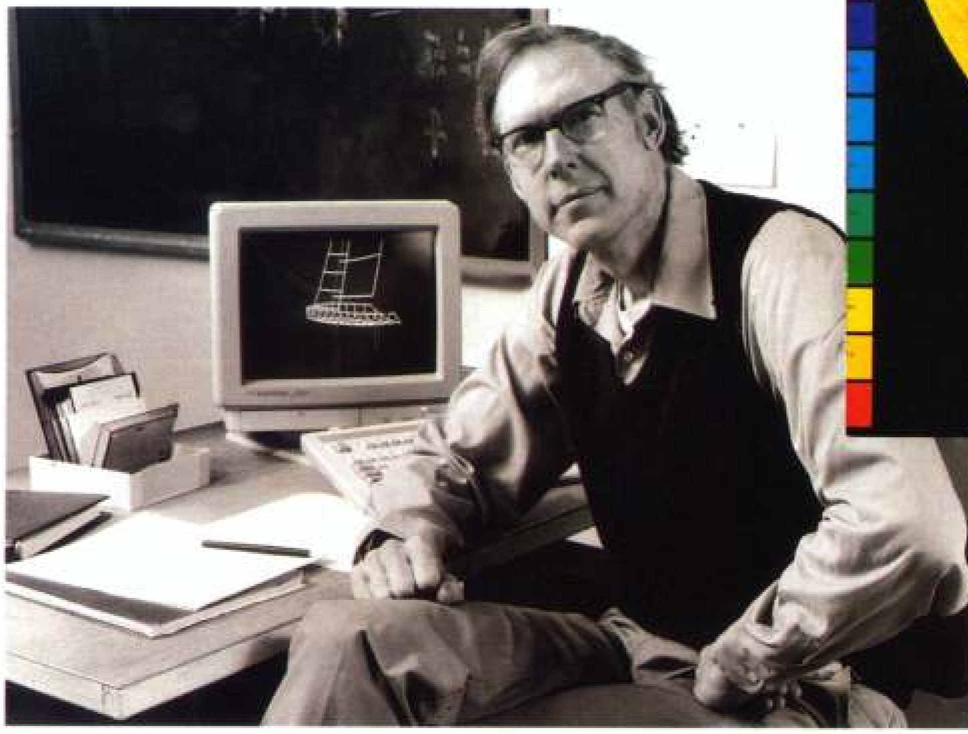
At about the same time Gentry was making a spectacle with his bubbles and tufts, another California scientist, John Letcher, was on a long voyage with his wife, visiting Hawaii, Alaska, Mexico, and the East Coast, sailing a 25-foot cutter of his own design. Letcher had already done a lot of intercollegiate racing and big-boat crewing, and had singlehanded to Hawaii and Alaska early in the '60s, after getting his honors degree in physics from Cal Tech. He went on to get his masters and Ph.D. from Cal Tech in aeronautics and applied mathematics, and later his M.S. in Naval Architecture from the University of Michigan.

Engrossed in sailing literature while trying to design his cutter, Letcher had run into the same problems Gentry had: "I researched the whole field of yacht design and found that it was really a primitive discipline compared with what I was getting in my aerodynamics courses. I immediately started seeing applications to sailboats, and ways of applying what I was learning about foils and flow and aircraft performance to sailing. I started working out theoretical tools that eventually led to the first VPPs. They didn't have a towing tank at Cal Tech, but the Civil Engineering department did have water channels where you could get a constant flow and I was putting instrumented models in that flow, and testing some of the questions that came up in my attempts to learn how to design a boat in a rational way."

Letcher was the lead scientist for Dennis Conner in the 1987 retrieval of the America's Cup from Australia. John Marshall, who was the manager of Conner's design team for that effort, and is now the manager of PACT 95, is unhesitating in his praise: "There's hardly anyone more profound in his understanding of the physics involved than John Letcher. He's been my mentor absolutely in this whole process of learning to manage these teams — it's basically a matter of going to school with him. When someone proposes a solution that promises an efficiency of 102 percent, I take them back and say, 'you know, John Letcher is going to be very surprised that you're saying Mother Nature is going to give you a grade of 102 on your paper.' You ought to be very suspicious when you're proposing a solution that's better than perfect. Letcher is extremely effective at puncturing balloons of that sort."

Of Snake Oil and Second Opinions

As is true in any time of transition from wishful science to real science — alchemy to chemistry, for example — this dawning computer age is a fine time for fast-talkers and bandwagon jumpers. Not surprisingly, Letcher takes a skeptical view of the apparent headlong rush toward science in the sport, especially as manifested in the rarefied atmosphere of IACC design. "There's so much secrecy in the America's



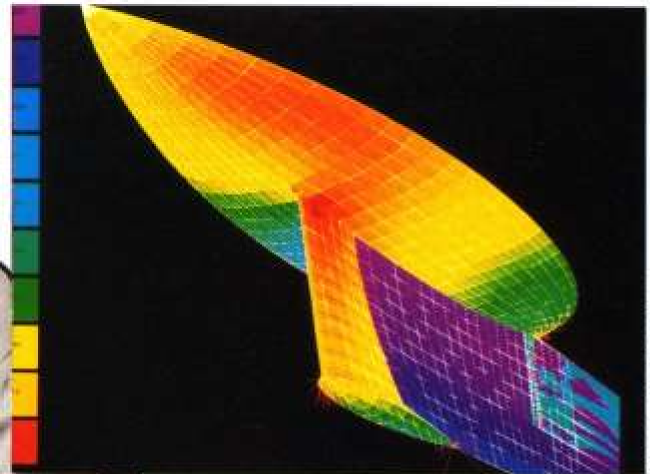


photo courtesy of AeroHydro

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– John Letcher

Cup work; nobody wants to reveal what he does or doesn't know, or doesn't understand. The technical content is pretty steep, and there's lots of opportunity for people who don't really know what they're talking about, but who can talk about it well enough to convince syndicate managers that they might be the key to success. I've had a chance to work with a number of these people on the same team, and have been at their technical presentations, and either they're holding their cards very close to their chest, or they don't have any cards. Many are steeped in the aerodynamics world and are not sailors; when you get these programs into the hands of naval architects who know the differences between boats and airplanes, then the number of experts who really understand how to do things right is very few."

How many is very few? A few hundred?

"I'd say you can count them on the fingers of one hand. Really."

Letcher mentions a recent sailing symposium at which someone with less-than-crystalline ideas was taken to task during the question period by Jerome Milgram of MIT. "Jerry just laid them low," says Letcher with a chuckle. "It was beautiful to see."

Milgram himself, Professor of Ocean Engineering at MIT and design team leader for the America[3] syndicate, has practiced hard-science naval architecture for many years, and has little patience with those who haven't double-checked their homework. In the case of the ill-fated symposium speaker, says Milgram, "His approach wasn't any good. A lot of these also-rans have somehow gotten into the sailing world, and have enough inherited ability as charlatans to convince people to use them. When you really look hard at the nuts and bolts of what they're doing, and think is it right or is it wrong, does it stand on a firm fundamental footing, you end up thinking, 'Gee, what am I doing dealing with this guy?'"

As a team manager, Marshall has faced such problems: "There are a lot of intentional or inadvertent snake-oil salesmen out there. I'm not exempt from having been fooled a few times."

When Letcher was the lead scientist for Marshall in the '87 Cup, he was, says Marshall, "the overall authority and arbiter of these sorts of discussions. It wasn't a case of charlatanism; a lot of times it's a case of taking a code which is admittedly a simplification of nature, pushing it, and being hopeful of getting a useful result, when close analysis would say that it's impossible to get a useful result."

Backpedaling is a natural part of the process, in both the design and engineering of cutting-edge boats. Steve Clark, chairman of Vanguard Racing Sailboats and leader of the "Cogito" project — the U.S. effort to win the C-Class catamaran title back from Australia — is, like Marshall, a team leader trying to juggle problems of theory and practice. "There's a design loop where you take practical information from the people who are building and using the stuff, and then you take a theoretical modeling of the problem, and if you're doing your job right you're sitting in the middle, listening to both sides, and trying to come up with a way of balancing them. You have to keep your sense of skepticism. Someone will come to you and say, 'I've run the numbers, and we can build this part at five pounds.' So you say, 'Oh really? That's great, that really helps. Now let's dig into this a bit...' And you find out that one way or another they're not using the real values, or something isn't lined up right, or it's something that can't be fabricated in the order that it needs to be made.

"You also have to ask whether you've written something wonderful, but that doesn't represent the world. Have we got the earth spinning the wrong way? An example: When we put the underhung rudders on *Patient Lady V*, Duncan MacLane and David Hubbard asked themselves how big the rudder shafts had to be. So they say, OK, what can the airfoil produce? They calculated the lift coming off the foil for the boat going 20 knots; and the side force the foil could generate was 'x.' All of a sudden the rudder shaft had to be solid-carbon-fiber two inches in diameter. Well, that didn't seem right, so they asked themselves what would happen if they applied a force like that to the back of the boat. And what would happen would be that the boat would be picked up and thrown through the air and do about three 360s in half a second. So, yes, the blade is capable of developing those kinds of forces, but no, there's nothing in the conditions that makes it necessary for it to have to do that."

Marshall acknowledges that at certain scientific levels, even an extremely well-informed sailing generalist is lost at sea: "That's the responsibility I give myself — to be well enough briefed in each of the core sciences, if not to know whether something is sound, to be able to get a second opinion, and, very importantly, to be able to work with scientists to devise experiments that will help elucidate the concepts. We do the best we can on the credentials of the individuals involved. When you're dealing with a senior scientist at Boeing you feel much more comfortable than with someone else, for example."

One of the scientists Marshall works with is Ed Tinoco, who oversees Boeing's technical support of both PACT 95 and Team Dennis Conner. Like Gentry, Tinoco is a Fellow of the Boeing Company. As Marshall points out, such a fellowship is an honor "given very sparingly to engineers who have a broad range of skills and are effective at pushing the technology envelope. Ed has been the resource at Boeing who helps us go shopping to identify which capabilities and tools are mature enough to be of likely value, and which tools need the intensive work to become the technology of the next round. He's a tremendously valuable resource."

While Tinoco is not a racing sailor himself, he's been out with his colleague Gentry on several sailing excursions. "On boats and airplanes we have a common interest in that last one percent of improvement," says Tinoco. "In an airplane that's a lot of fuel over the years. On boats it's the difference between winning and losing."

Comparing the nature of his work on airplanes versus America's Cup boats, he says the major difference is in the deadlines. "We've really been amazed at how quickly these guys can put concepts into hardware and into the water. An airplane program may go for a number of years before the thing finally takes to the air. Even a wind tunnel program usually takes six months. But the sailors are doing one-of-a-kind vehicles, and the materials they deal with allow them to work in that shorter time span. A keel that you can hog out of a solid piece of metal can be done a lot faster than if you have to build up a very complex structure to maximize strength and minimize weight."

Milgram is somewhat less indulgent: "Technically there's no difference; the only difference is that the people who do it make you work in a state of panic; you can't plan ahead very well. It's awful."

Says Tinoco: "In February, '92, Dennis Conner came to us and said, 'Hey, we're in trouble; we need a better bulb and keel.' We designed it in three days' time and it was on the boat in 24 days."

Tinoco goes on to relate that at about the time Conner's crew had finished attaching the 24-day wonder to the boat, wind-tunnel test results came into the DC camp from General Motors, suggesting that the new keel would actually produce more drag than the old one. "Conner's team hadn't faired it out yet," says Tinoco, "but they'd bolted it on the boat and they had to start racing in about two days. They had enough time to put the old keel back on, or they could go with the new one. They called us up and faxed us the data, and we had to make the decision that afternoon."

Boeing stuck to its guns, Conner kept the new keel, and it turned out to be that significant fraction faster than the old one.

None of this, Tinoco is quick to point out, reflects badly on GM's wind-tunnel testing. "The difference is in the testing technique and what you're trying to do. At GM, they're not in the business of testing to get that last quarter-of-a-percent value; so their techniques are a little different than what we use in the airplane industry. In looking over how they did their tests, we felt there was enough leeway there that we didn't choose to believe the drag number."

"That's true, you know," says Milgram. "When you design a car, you don't care about half a percent, even in a race car, but in a sailboat it's everything."

Proving the Methods

Marshall points to the 1987 America's Cup as a defining moment in the watershed, when he brought a kind of systems analysis approach to Conner's recovery effort. "Starting with that program," says Marshall, "there was a sea-change in the way boats are designed in the United States. We stepped away from the idea that a single naval architect's office would do the entire job, and moved into an environment where we said we needed a design team that embraces three components: first, a lead naval architect who integrates all the input and is ultimately responsible for the design; second, strong university relations. In the university environment you find the theoreticians who can extend the science further, and the experimentalists who can carry out wind tunnel or towing tank or other kinds of experiments to validate the computer code predictions. In many cases the code development goes on in the university as well. The third component is the major, high-technology corporations that do simulation technology work on a regular basis."

In that mix of disciplines, the science that eventually makes its way to the top is old-fashioned, rigorous science: absolute honesty in calculations and experiments, with all the rest thrown out. Even then errors are expected, and doubts are rampant.

As Marshall says of CFDs, "Every code is an explicit simplification. When you go onto the computer, you consciously leave out part of the picture, part of the physics. The art form is to decide what you can leave out and still get a useful answer. It won't be a right answer, by definition, but it may be a useful answer. The only reality is out on the water, and it's far too complicated to put all that in a computer."

Marshall outlines the thought process of the early stages of his current PACT campaign, showing that *Young America*'s final design sprouted from a carefully cultivated field of well-explored problems: "We say, OK, we need to have an understanding of the rough-water performance of boats...The idea is not to develop a series of candidate America's Cup boats, but a series of hulls or forms that explore the different areas where theoretically the code might be expected to be weak. Then, with people like John Letcher coming into the dialogue and applying their insight into the potential problems of a particular formulation, you go into an experimental environment, in this case the University of Michigan towing tank, with a set of hulls that are not candidate boats, but that do have characteristics that would be known to be troublesome to that type of code, and that cover the range of forms you might expect to find in the America's Cup class. They're relevant, but they're not candidate designs. In this way you validate the code, and you calibrate it. It may be that you find exact correspondence, but that's rare. More often you find good quantitative trending. You do a build-up. You start with the very simple case of a stripped hull, and you make obvious changes to it, such as redistributing the weight from the middle to the ends, and see how well the code handles that single variation. Then you might change the vertical center of gravity by moving the weight up and down. How well does the code handle that? Then you might take ballast out or put it in, so you have a displacement change on the same hull form. After you've explored that single hull form pretty extensively, and several others that differ in their slenderness, or their overhang treatment, or the flare in the topsides — all the basic parameters that drive rough-water performance — maybe then you're ready to go back and put appendages on and start exploring the ability of the code to capture their effects."

The labor loop of refining codes, to refine forms, to refine VPPs, is an intense exercise, as draining in its own way as recalculating all a boat's numbers by hand in the old days. In the build toward the 1987 Cup challenge, once Conner's design team had drafted the lines for a candidate hull and appendages, Letcher found that "the process of creating an input file for the flow analysis was very tedious — it would take a very skilled person days of work to create it for just one model,

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and in order to vary that model a good part of the work would have to be done over. The process of creating geometric shapes to use as input to the flow analysis was a bottleneck."

Today Letcher runs a company called AeroHydro in Maine. Among other programs, Letcher is responsible for MultiSurf, which the late Gary Mull once hailed as "the first truly useful 3D design program." MultiSurf can be used to design all the geometric forms of a boat (or a car, or a wheelbarrow), but it really shines in its ability to recalculate and update all associated values when a single detail is changed. Moreover, says Letcher, "one of its forms of output is geometric data that's in the required format to go into a fluid dynamics analysis program. It allows you to vary the shape of your original models, create systematic series of design variations, and the CFD input is almost instantaneously generated." So at least one 1987 bottleneck has now been opened.

The Wider Spout

To most people sailboat racing is, at its most brilliant, a sidelight in the sports news. But at a certain conscious level, of course, making a vehicle move across the interface of air and water is a sublime intellectual exercise. Anyone who fails to recognize the power of the wind, and the power of the sailing vessel, to bring inventive, aggressive minds to bear at the frontier of nature and science, knows little of the history of the world, and possibly less about its future.

"During the energy crisis," says Letcher, "a good deal of work was done, some by me, on the potential for commercial sailing ships. A lot of promise was revealed, but then the petroleum prices went down again and the whole field dried up. They could well be useful in another 20 or 30 years if we actually manage to burn up all the oil. I hope they keep enough of it around to make some Dacron sails."

The view is the same from Clark's hard-sail vantage point: "At some point the question of extracting energy from the atmosphere in order to move vessels around may become more relevant. In the short term you're refining something only for a sporting goal, but it may have broader implications later. That's one of the fun things about it. You're figuring out low-speed airfoils. You're figuring out something about this gas that flows by every day, this sustainable energy..."

"We're talking about a way of thinking about problems in nature in a technical society," says Marshall. "What's most important to me is seeing young people prepared to be more responsible adults and voters in the future. It drives me up the wall to see the major social issues that are heavily technically loaded being debated on a completely irrational basis. You don't have to be an engineer; it's a matter of being literate in the language of our society."

Says Clark: "We're not necessarily as creative as we should be, but one would hope that on some level what the aircraft aerodynamicists and sailing aerodynamicists and windmill aerodynamicists are doing would criss-cross."

It doesn't seem such a far-fetched idea. But to let the heretics have the last word, we pose to Letcher and Gentry a simple question: Why do you sail? What thrills you about it?

"In 1963," says Letcher, "there was so little technical literature about boats, and so much of it was way off the track, that I think it's fair to say that nobody in the world knew how they worked. Just the sailing thrills me — trying to understand it has been a theme of my whole adult life."

Gentry: "I went sailing one day with a friend on a Saturday afternoon on a little lake in California, and I was hooked. This was wind, and this was water, and this was a game I could play."

Doug Logan is Consulting Editor to Sailing World.