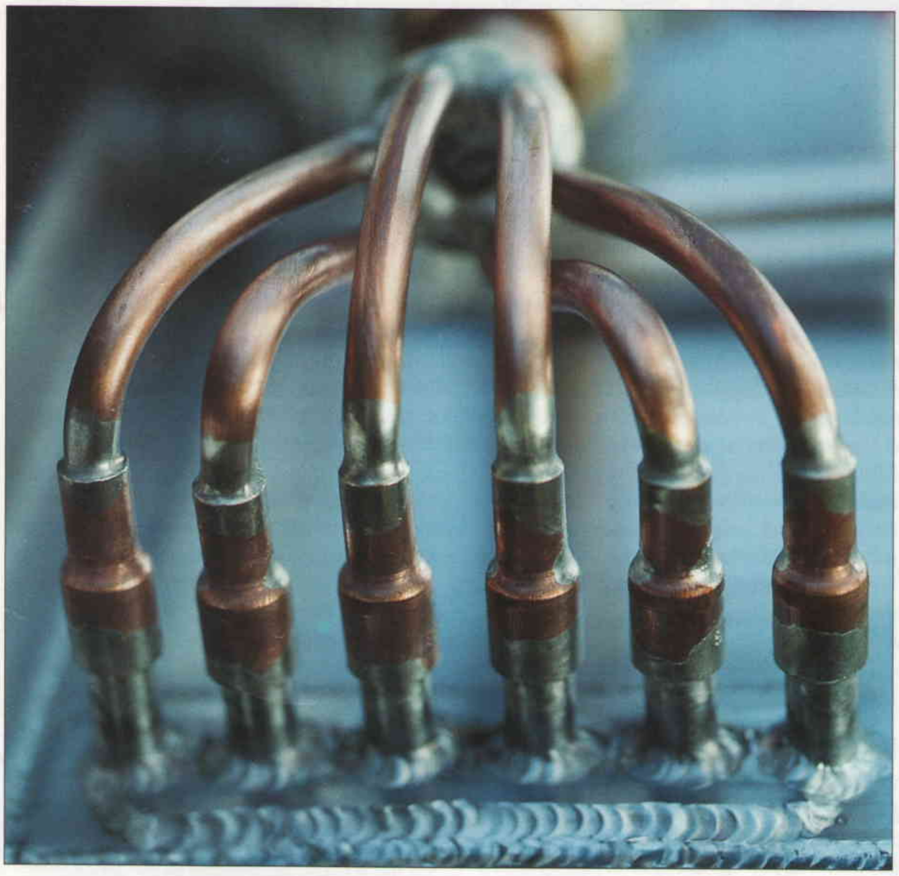
PROFESSIONAL BOATBUILDER



Marine Refrigeration Part Two

We look at the systems currently available for AC, DC, and engine-driven refrigeration.

Text and photos by Nigel Calder

In the last issue of *Professional BoatBuilder,* we saw how to determine the heat load, or energy demand, of a given icebox in refrigerator or freezer use. The next step is to choose which kind of refrigeration unit will best meet this demand.

Refrigeration is not something that can just be tacked onto a boat. It is a major power consumer, particularly in warm climates, where DC refrigeration— the most common type—can account for 50% to 75% of a boat's total DC demand. *A refrigeration unit must be carefully integrated into a boat's available power supplies,* which in turn are a function of the use to which the boat is put. A boat that cruises on weekends, for example, will have shore power available in its slip all week, whereas one used for long-term offshore cruising will not. It may well be the case that two identical production-line boats with similar-capacity refrigeration demands are best served by radically different types of refrigeration units.

A boat with a 24-hour-a-day AC generator can obviously use household-style AC refrigeration units; less common is holding-plate AC refrigeration. In the absence of a constant source of AC power, there are three popular refrigeration choices: engine driven (with holding plates), constant-cycling DC, and holding-plate DC.

AC Refrigeration

Constant-cycling AC refrigeration requires a constant source of AC power. On a boat where the generator runs 24 hours a day, it is the cheapest and simplest option, in part because it can run on household appliances. Don't confuse generator-supplied AC power with that supplied by a DC-to-AC inverter. Any attempt to run AC refrigeration from an inverter will result in substantially greater energy losses than in most other systems. It would be better to install a DC system.

Holding-plate AC refrigeration requires intermittent operation of a generator. It employs one or more tanks filled with a solution having a freezing point below that of water. The tanks are fitted to the icebox. When the refrigera-

The top of a Glacier Bay holding plate, showing the manifold for its proprietary evaporator coil ("Spider Coil"). A holding plate has an evaporator coil—a coil of tubing through which refrigerant passes—immersed in a tank of fluid. The evaporator coil freezes the liquid in the tank, which then melts, absorbing heat from the icebox.

The refrigerator/freezer setup on the author's own boat. ***Left—****The flat-plate evaporator in the icebox, shown here, takes up less space, and weighs less, than a holding plate, but requires a constant-cycling refrigeration unit. In an evaporator plate, the evaporator coil consists of a series of passages formed between thin sheets of aluminum sandwiched together; there is no tank of fluid, so the evaporator plate is much smaller and lighter than a holding plate. The evaporator plate absorbs heat directly from the air in the icebox.* ***Right—****Details of the freezer: note the double seals on the lid, the flat-plate evaporator bent around three sides on the inside, and the ice tray held to the evaporator with bungee cords.*

tion unit is running, it freezes the solution in the tanks, and then the unit shuts down. The tanks slowly thaw, absorbing heat as it leaks into the icebox, keeping the box cold. When the tanks have almost defrosted, the unit is turned back on to refreeze them. In a well-designed system, the tanks will hold down the temperature in the icebox for 24 hours—even in the tropics—and will then require no more than one to two hours' refrigeration running time to be refrozen.

Running an engine in order to spin a generator that powers an electric motor that spins a refrigeration compressor that could have been driven directly off the engine in the first place involves a lot of unnecessary energy losses! What's more, the directly engine-driven compressor will, in most instances, have a higher output than the AC unit, and therefore a potentially reduced holding-plate pull-down time, depending on whether or not the holding plates can absorb additional compressor output (see "Engine-driven Refrigeration," below).

In other words, it's rarely worthwhile to run a generator simply for refrigeration purposes, but if the generator is to be run for other loads such as water making, water heating, or cooking regularly enough and long enough to support the refrigeration system, *and* has surplus capacity that can be diverted to AC refrigeration, then holding-plate AC refrigeration is attractive. The AC unit will, of course, be operable with shore power. It will also have a hermetic compressor, so that the system can be sealed, and will not suffer from the small leaks that sometimes plague the belt-driven compressors used in engine-driven, and most high-capacity DC, refrigeration systems. The AC system will take a substantial load off the DC system. That means that on some boats, the battery banks and other equipment can be downsized, with significant savings in weight and volume.

Engine-driven Refrigeration

Engine-driven systems have holding plates, but the refrigeration compressor is directly belt driven from an engine instead of being driven by an electric motor, eliminating the intermediary energy losses. These systems almost invariably have automotive air-conditioning compressors, resulting in extremely high nominal refrigerating and freezing capabilities. One example of such a system is from Sea Frost. (Contact information for all the companies mentioned in this article is on page 55.)

The beauty of such a system is that the horsepower available with most engines allows for a large and powerful refrigeration compressor, minimizing the holding-plate freeze-down time and engine-running time. Given that the compressor is directly driven by the engine, engine-driven refrigeration also appears to be the most efficient.

Unfortunately, for refrigeration systems of the size commonly found on pleasure boats, neither of these propositions—power and efficiency—is necessarily true! The reason is related to the rate at which heat can be withdrawn from a holding plate; that is, the rate at which the plate can be frozen. This rate is largely a function of the surface area of the evaporator tubing in the holding plate, the spacing of these tubes (the closer together, the faster the rate of heat removal), and the temperature differential between the refrigerant in the evaporator coil and the solution in the holding plate.

Except in large systems with multiple holding plates, the rate of heat removal is always well below the nominal refrigerating capability of the compressor on the system. In other words, *no matter what size refrigeration compressor you put on the engine, only a certain amount of its capacity can be used, and the holding-plate freeze time cannot be accelerated beyond a certain point.* (Note that the holding plates made by Glacier Bay have the highest heat-absorption capability of any on the market.) This, in turn, means that regardless of compressor capacity, for most systems the engine will have to be run at least an hour a day, and almost always longer. In the tropics, two hours or more is common.

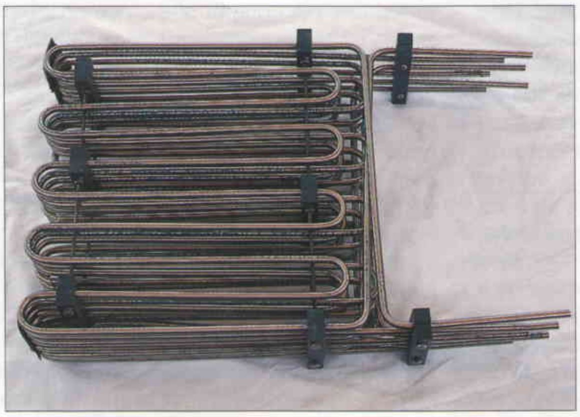
If a high-output alternator is installed on the same engine, wired to a large enough battery bank to absorb the alternator's output, then sufficient energy can be put into a battery bank to meet the daily refrigeration load in less engine-running time than is needed for engine-driven refrigeration. That's even with the added inefficiencies in DC refrigeration (the alternator charges batteries that supply an electric motor that spins a compressor that could have been turned by the engine in the first place). In other words, *if minimizing engine running time is a goal, the DC approach often does a better job of capturing the available power from the engine than does the engine-driven* *approach.* The net result is that although from a refrigeration perspective DC refrigeration is less efficient, from a whole-boat energy analysis it will be more efficient on those boats where the goal is to minimize engine-running time.

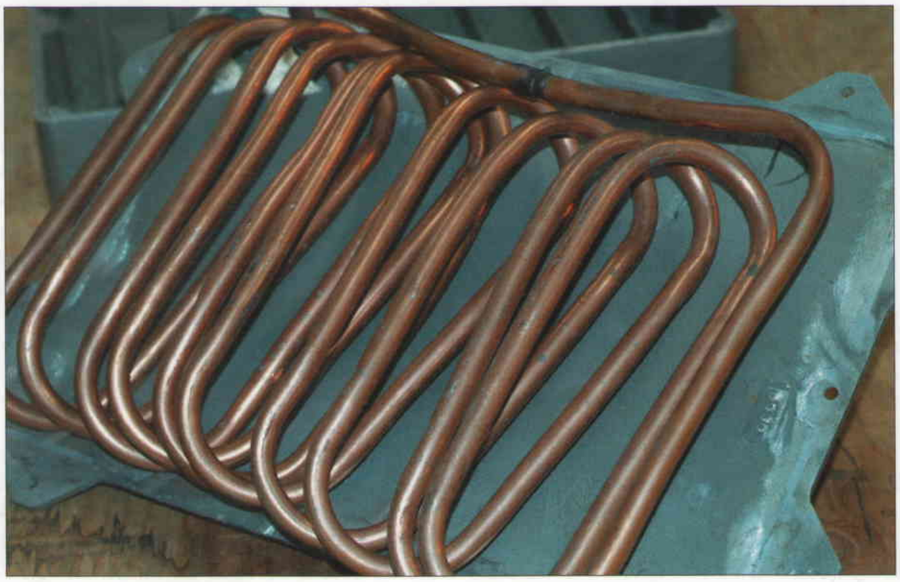
Consider also the fact that the typical cost of purchasing even a small marine diesel engine and having it professionally installed is anywhere from $12,000 on up, with a life expectancy of anywhere from 5,000 hours of running time on up. As a result, the capital cost—excluding maintenance and fuel bills—of running the engine is almost always at least $1 an hour, and all too often can be $3 an hour or more. That's a significant overhead if the engine is being run solely for refrigeration purposes.

As noted, this argument breaks down if the engine will be regularly run for other reasons—as it is, for example, on many charter boats. In such cases, engine-driven refrigeration can be tacked on as just another load. The argument also does not hold in the case of large iceboxes with multiple holding plates that have the capacity to absorb a high compressor output. In this situation, engine-driven refrigeration may be the best choice. However, it does suffer from one other major drawback: even at dockside, the engine must be run in order to refrigerate.

For those times when the engine is not running, or the boat is at dockside, an engine-driven system can be combined with a DC or AC system by adding a second evaporator coil to the holding plates. The trade-off here is the ability to run the unit at dockside without cranking the engine, versus the added complexity and cost, as well as the volume of the holding plate occupied by the second evaporator coil. (The increased volume reduces the plate's overall capacity, and sometimes reduces the length—and therefore the rate of heat removal—of the primary, engine-driven, evaporator coil.)

Although expensive, an engine-driven unit will compare very favorably in terms of cost with high-capacity DC systems, and even with small DC systems if the boat's batteries and charging systems have to be upgraded to support DC refrigeration. In the latter case, given the weight and bulk of the added batteries, the engine-driven system will be lighter and take up less space.





***Left**—Glacier Bay's Spider Coil. **Below**—The evaporator coil from a Seafrost holding plate. The Seafrost coil is a continuous run of relatively large-bore copper tubing coiled up inside the plate, whereas the Spider Coil has six lengths of much smaller-bore copper tubing coiled in parallel inside the plate, and terminating at an inlet and outlet manifold.*

Constant-cycling DC Refrigeration

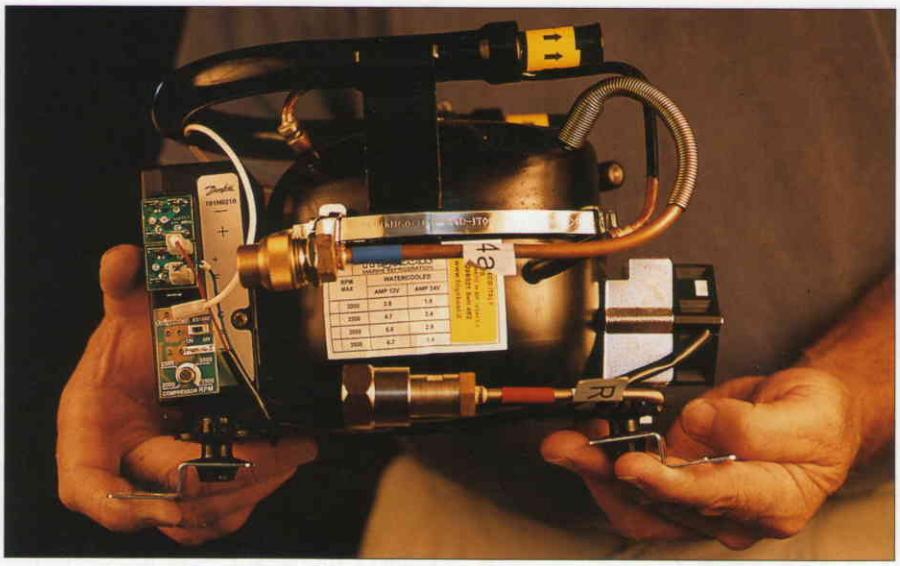
A small refrigeration unit is permanently connected to the ship's batteries and controlled by a thermostat in the icebox. Every time the temperature rises beyond a set point, the unit kicks on until the icebox is cooled down, and then the unit switches off. It constantly cycles on and off, just as a household refrigerator does.

Aside from household appliances, constant-cycling DC refrigeration is the cheapest initial option. Norcold and other manufacturers build drop-in units, similar to household refrigeration units. Many of these drop-in units can also be run off AC power when available. Or, a refrigeration unit is added to a purpose-built icebox. Either way, most units currently available use Danfoss BD35 and BD50 variable-speed compressors with HFC-134a refrigerant.

These systems have a limited refrigerating capability. I would consider the upper limits to be 5,000 Btu per day in a refrigerator, and 3,500 Btu per day in a freezer. (One Btu is the amount of heat needed to raise 1 lb of water by 1°F. The metric equivalent is a calorie [small "c"] or Calorie [large "C"], the amount of heat needed to raise 1 gram [small "c"] or 1 kg [large "C"] of water by 1°C. Four Calories [large "C"] = 1 Btu.) This refrigerator number is much higher than I have previously recommended, while I have in the past recommended against constant-cycling DC freezers. The capacity and efficiency of the Danfoss compressors have increased significantly over the past 10 years.

• ***Constant-cycling capacity calculations.*** Just as with many engine-driven systems, for many of the latest- generation constant-cycling DC units, the limiting factor in the system is not the compressor's capacity but the rate at which the evaporator plate can pull heat out of the icebox. For the typical aluminum evaporator plate (similar to what is in a household refrigerator), this is somewhere between 1 and 7 Btu per square foot, per degree F temperature differential between the plate and the icebox, per hour. The huge range I have given—from 1 to 7 Btu—reflects a lack of good data, differences in evaporator construction techniques, and the insulating effect of ice buildup on the plates. Assuming 3.5 Btu is conservative in most applications.

Let's imagine an evaporator plate with a total surface area of 3 sq ft (0.28m^2), with a temperature differential of 25°F



***Left*—Shown here is one of the largest flat-plate evaporators for boat refrigeration systems currently available, from Frigoboat. It can be bent to wrap around the inside of an icebox. *Above*—A Danfoss BD50 compressor for a Frigoboat constant-cycling DC system.**

(14°C) between the plate surface and the icebox interior. (Twenty-five degrees F is a reasonable assumption for a refrigerator; on a freezer, a 15°F (9°C) temperature differential would be a better number.) Such a plate will remove around 260 Btu per hour (3 x 25 x 3.5 = 262.5). If the refrigeration unit is running for 45 minutes per hour, the total amount of heat removed in 24 hours will be (262.5 x 24 x 45)/60 = 4,725 Btu.

We can work this backward. Let's say we have an estimated heat load of 5,000 Btu on a refrigerator (the maximum I recommend for constant-cycling DC refrigeration), and we want to limit refrigeration run time to 45 minutes per hour. Every hour we must remove 5,000/24 = 208 Btu of heat. To keep the running time to 45 minutes per hour, the rate of heat removal must be (208 x 60)/45 = 278 Btu per hour. (In terms of watts per hour, this is 278/3.413 = 81.4 watts per hour.) If the temperature differential between the icebox interior and evaporator plate is 25°F, we need an evaporator plate with a surface area of 278/(25 x 3.5) = 3.18 sq ft (0.3m^2). This is a moderately large evaporator plate—although maybe not as big as it seems, because in many situations both surfaces will be absorbing heat, doubling the effective surface area. Nevertheless, its size indicates that we are approaching the practical limits of the system. If the evaporator plate is smaller, the refrigeration unit will run longer.

Calculating the same numbers for a freezer that has a heat load of 3,500 Btu (once again, the maximum I recommend), and a temperature differential of 15°F, with a 75% duty cycle (i.e., the refrigeration unit runs 45 minutes in the hour), we end up with an evaporator plate area of 3.7 sq ft (0.34m^2), if only one surface is absorbing heat. The plate will almost certainly be mounted on stand-offs, so both sides will be absorbing heat, in which case the plate needs to be approximately 2 sq ft (0.19m^2).

Let's assume we are using one of the largest plates commonly available (made by Frigoboat), which is 40″ by 16″(40cm by 101cm). That's 4.4 sq ft on each side (0.44m^2). If mounted on stand-offs, its heat absorption rate in a freezer is 4.4 x 2 x 15 x 3.5 = 462 Btu per hour, which is (462 x 45)/60 = 346.5 Btu on a 75% duty cycle. This results in a potential heat absorption of 346.5 x 24 = 8,316 Btu per day. (Note that Isotherm supplies evaporator plates up to 59″ x 17″[43cm x 150cm]).

In practice, at the kind of temperatures found in freezer applications, the refrigeration compressor will not have anywhere near the capacity to pull down the plate at a rate of 462 Btu per hour. As **Table 1** shows, the lower the evaporator temperature, the lower the capacity of a compressor. In our example, the compressor has now become the limiting factor in the system; the refrigeration run time will be commensurately longer. (Note, however, that Danfoss recently introduced the BD80 compressor; it has 50% more capacity than the BD50, on which the tables below are based.)

Let's take a Danfoss BD50 in a freezer application. We want to hold the box temperature at 10°F (–12°C). We assume a 15°F temperature differential between the box and the evaporator plate, which means the plate is at –5°F (21°C). Using the –10°F column in Table 1 (because there is no –5°F column), we find the maximum rated output of the compressor at this evaporator temperature is 245 Btu per hour. For a 3,500 Btu capacity the unit will run for 3,500/245 = 14.3 hours. To handle this compressor output, we need an evaporator plate with a minimum surface area of 245/(15 x 3.5) = 4.7 sq ft (0.44m^2), or 2.4 sq ft (0.22m^2) if mounted on stand-offs.

Please note that these are pretty crude numbers based upon arguable assumptions. Nevertheless, the methodology outlined provides a mechanism for calculating evaporator plate sizes and approximate refrigeration-unit running times, from which the approximate load on the DC system can be calculated.

• ***Power drain.*** In terms of power consumption, a good general rule is:

In *refrigeration* use, with an air-cooled system, assume 5.0 Btu of heat removal for 1 watt-hour of energy consumed. That is, 5,000 Btu = 5,000/5.0 = 1,000 watt-hours, which is 1,000/12 = 83.3 Ah at 12V, and 1,000/24 = 41.6 Ah at 24V. (The rate of heat removal per watt of energy consumed will be somewhat higher with water cooling.) Remember to add at least 10% for inefficiencies in the charging process.

In *freezer* use, assume 4.0 Btu of heat removal for 1 watt-hour of energy consumed. That is, 3,500 Btu = 3,500/4.0 = 875 watt-hours.

Table 2 gives more-precise numbers for air-cooled systems based on reasonably conservative performance numbers. With water cooling, the heat removal will be somewhat higher. I'll go into detail on air-cooled versus water-cooled systems below.

Table 1: **Danfoss BD50 Vital Statistics: Capacity in Btu (Watts) per Hour**

Compressor RPM	Evaporator Temperature (°F/°C)					
	-20F/-29C	-10F/-23C	0F/-18C	10F/-12C	20F/-7C	30F/-1C
2,000	95 (28)	142 (42)	201 (59)	273 (80)	359 (105)	458 (134)
2,500	119 (35)	176 (52)	247 (72)	335 (139)	442 (130)	570 (167)
3,000	142 (42)	211 (62)	296 (87)	401 (117)	529 (155)	682 (200)*
3,500	167 (49)	245 (72)	342 (100)	464 (136)	612 (179)*	790 (231)*

Table 1 assumes a condensing temperature of 130°F (55°C), an ambient and suction gas temperature of 90°F (32°C), and a liquid temperature of 90°F, which is the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) standard. For refrigeration applications, the 0°F or 10°F column is a reasonable capacity guide; for freezer applications, use the –10°F column.
*Fan-cooling of control module required.

Table 2: **Danfoss BD50 Vital Statistics: BTU of Heat Removed per Watt-hour of Energy Consumed**

Compressor RPM	Evaporator Temperature (°F/°C)					
	-20F/-29C	-10F/-23C	0F/-18C	10F/-12C	20F/-7C	30F/-1C
2,000	3.49	4.09	4.81	5.57	6.31	7.00
2,500	3.47	3.97	4.58	5.28	6.05	6.88
3,000	3.43	3.93	4.55	5.26	6.05	6.89
3,500	3.37	3.91	4.54	5.23	5.94	6.66

Table 2 assumes a condensing temperature of 130°F (55°C), an ambient and suction gas temperature of 90°F (32°C), and a liquid temperature of 90°F, the ASHRAE standard. For refrigeration applications, the 0°F or 10°F column is a reasonable guide; for freezer applications, use the –10°F column.

Table 3: **Danfoss BD50 Vital Statistics: Current (Amp) Consumption at 12V**

Compressor RPM	Evaporator Temperature (°F/°C)					
	-20F/-29C	-10F/-23C	0F/-18C	10F/-12C	20F/-7C	30F/-1C
2,000	2.28	2.87	3.50	4.18	4.90	5.65
2,500	2.86	3.65	4.45	5.26	6.10	6.94
3,000	3.52	4.43	5.37	6.33	7.31	8.32
3,500	4.20	5.18	6.24	7.39	8.61	9.91

COURTESY DANFOSS

Above—*Tables 1, 2, and 3 provide data for calculating evaporator plate sizes and refrigeration-unit running times, from which the approximate load on the DC system can be calculated.*

Table 3 gives the current consumption of a BD50 compressor when running on 12V. (For 24V, halve these numbers.) Note that the slower the compressor's operating speed, the more efficient it is—that is, the more Btu of heat are removed from an icebox per watt-hour of energy consumed. There are significant benefits to be had from running a compressor longer hours at slower speeds, rather than shorter hours at higher speeds. For more on why this is, see the section "Smart speed controllers" on the next page. Whatever the load, unless there is some type of continuous battery-charging device that keeps up with the demands of the refrigeration unit, this kind of battery drain will cycle the ship's batteries on a daily basis. The batteries on a boat used for weekend cruising can be recharged at dockside during the week, but on those boats that engage in more extended cruising, if there is no constant battery-charging source (either from running the boat's main engine on a powerboat, or from a battery charger powered by an AC generator), then a high-capacity DC system is needed to support the refrigeration load. Such a system might include deep-cycle batteries, a high-output alternator, a multistep regulator, and maybe a wind generator with backup solar panels. If not already installed, this type of DC system will cost several times more than the constant-cycling DC refrigeration unit!

Constant-cycling DC refrigeration is therefore an appropriate choice on a boat with relatively modest refrigeration needs, one that is to be cruised on weekends, one that has continuously operating battery-charging devices, or one that already has a high-capacity DC system. Given a powerful-enough DC system, large refrigeration needs can be met through multiple units and iceboxes. If the heat load of a large icebox exceeds the capacity of a single constant-cycling refrigeration unit, two or more units can be installed.

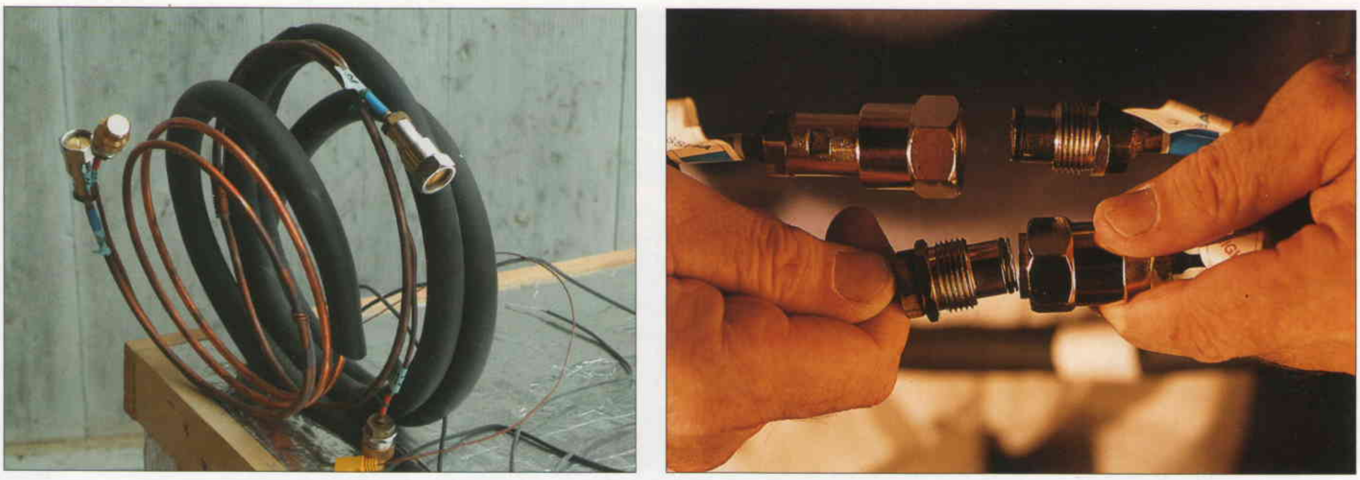
An increasing number of constant-cycling DC units come precharged with refrigerant, with the various subcomponents precharged, and a variety of quick-connect fittings that allow the installer to assemble the unit more or less without the use of tools, and without having to evacuate and charge anything. All these features greatly simplify installation and are excellent innovations. If the connections can also be undone without losing the refrigerant charge (some can), then a boat owner in a remote location can change out subsystems without specialized equipment—a very handy feature.

- ***Smart speed controllers.*** The slower the Danfoss BD50 and BD35 compressors are run, the more efficiently they operate (see Table 2). Whereas in the past, much refrigeration design work was premised on running compressors at full speed for a 50% duty cycle, the focus nowadays tends to be on running the compressor at lower speeds (and outputs) closer to 100% of the time. To do this, Frigoboat has developed what it calls its Smart Speed Controller (SSC), while Danfoss has Adaptive Energy Optimization (AEO).

The AEO starts a compressor at around its mid speed (2,600 rpm) and then ramps up the speed 12.5 rpm every minute. In other words, the speed increases by 12.5 x 10 = 125 rpm every 10 minutes. If the icebox has not been pulled down to the thermostat's shutdown temperature within 60 minutes, the compressor is switched to full speed (3,500 rpm).

Once the shutdown temperature is reached, when the unit is restarted it does so at the shutdown speed minus 400 (in this case 3,500 – 400 = 3,100 rpm) and then ramps up again at 12.5 rpm every minute. After the initial pull-down from a warm box, the icebox should be cold, so the unit will not run long enough to increase the speed by 400 rpm before it shuts down again. Let's say it stops at 3,300 rpm. Next time it starts, it will do so at 3,300 – 400 = 2,900 rpm.

The compressor is now starting from a slower speed, resulting in a lower refrigeration output, so it will take longer than the last time to pull down the icebox to the shutdown temperature. But, it will still probably not run long enough to



***Left*—Precharged refrigerant lines. The installer has only to screw the various system components together *(right)*; no vacuuming-down or charging with refrigerant is required.**

increase the speed by 400 rpm, so the next time it restarts it will be even slower, and the pull-down time will be even longer. It keeps this up until the pull-down time is 32 minutes, at which point it reaches equilibrium. Over 32 minutes, if the speed increases at 12.5 rpm per minute, the total increase is 12.5 x 32 = 400 rpm; this then drops 400 rpm at the next start.

The process extends compressor running times, but at reduced speeds, significantly boosting overall efficiency. It has the added benefit in warm climates, when the head pressure on a compressor is high at startup, of keeping down the initial load on the compressor. This greatly reduces the risk of compressor-electronics burnout—one of the more common causes of failure on older systems.

Any time the power to the unit is shut down (as opposed to the thermostat shutting it off) the controller starts the process again (i.e., at 2,600 rpm). Some controllers have a manual override that enables the refrigeration unit to be switched to continuous full output until manually reset to "automatic"—a useful feature if the boat owner loads the icebox with warm produce.

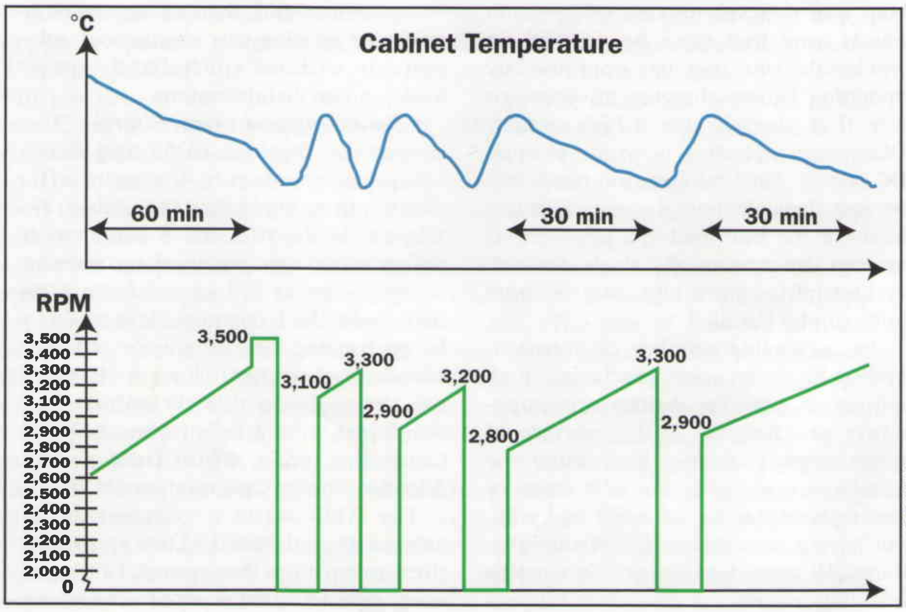
The Frigoboat SSC is similar to Danfoss' AEO in that it ramps up the compressor speed from a relatively slow start. It measures the time it takes to pull an icebox down and compares this to an "ideal" operating profile, adjusting the compressor speed accordingly. The aim is to keep the compressor running for approximately 50 minutes in the hour. Rob Warren of Frigoboat says the ideal would be to keep the compressor running continuously and then vary the speed to match the load, but he feels that customers would be disconcerted by the lack of any shutdown time.

Isotherm has a different approach to improving overall energy efficiency. Its Automatic Start Up (ASU) unit senses battery voltage, and any time it is above 13.2V (on a 12V system) the ASU turns the compressor to its full speed. The assumption is that when battery voltage is above 13.2V, a charging device is operating (alternator, battery charger, or some other device) and thus it makes sense to run the system as hard as possible. Even though this may not be the most efficient way to run the compressor, it is the most efficient way to operate the energy systems as a whole. A similar approach is used by several manufacturers with holding-plate systems, "topping off" the plates whenever a charging device is online.

Air-cooling vs. Water-cooling

Most constant-cycling DC refrigeration units come with an air-cooled condenser—the vital component that dissipates the heat taken out of an icebox. In warmer climates the air temperature in a closed-up boat can rapidly climb to 100°F (38°C) or more, rendering an air-cooled condenser increasingly ineffective just when the refrigeration demands of the icebox are at their greatest. Unless the condenser is built with a large enough surface area to handle the

Danfoss' so-called Adaptive Energy Optimization for its compressors goes through a programmed cycle that causes the compressor to run for longer periods of time at lower speeds than would normally be the case. This significantly raises the overall efficiency of the compressor. The graph shows the relationship between cabinet temperature and compressor speed. The latter is controlled so that the thermostat run time will be approximately 30 minutes.



COURTESY DANFOSS

high ambient temperature (many are not), the unit will start to run almost continuously, draining the batteries, perhaps still not refrigerating properly, and with a distinct risk of burning up the compressor. If a boat is likely to venture into warmer climates with air-cooled refrigeration, *the surface area and the thickness of the condenser become key considerations.*

The efficiency of any air-cooled condenser can be substantially improved if the temperature of the cooling air is lowered and/or the speed of the airflow over the condenser is accelerated. If a boat is to cruise in warmer climates, at the least some thought should be given to ducting in air from the coolest part of the boat, and achieving the greatest possible airflow over the condenser. WAECO Adler/Barbour, Sea Frost, and other manufacturers offer add-on ducting kits. WAECO calls its product a Powerduct Kit.

The other option, if an existing condenser is undersized, is to fit a water-cooled condenser. Water is a far more efficient cooling medium than air, and even in the tropics the water temperature rarely exceeds 85°F (30°C).

If the water-cooling circuit requires a water pump (not all do—see below), the critical ambient air temperature at which water-cooling becomes more energy efficient than air-cooling is generally around 95°F (35°C)—despite the added energy consumption of the water pump attached to the water-cooled condenser. Note that this temperature is the temperature *in the space occupied by the air-cooled condenser,* or of the air used to cool the condenser if the air is ducted in from elsewhere—*not* the temperature in the boat, which may be considerably cooler.

Below 95°F (35°C) ambient air temperature, a pump-driven water-cooled condenser is often less efficient than an air-cooled condenser (especially a well-designed one) in overall power consumption, because of the added power drain of the water pump. As the temperature rises above 95°F, water-cooling becomes progressively more efficient; by 110°F (43°C) it is significantly more efficient.

The question then becomes: at what point does the increasing efficiency of water-cooling justify the added expense, installation requirements, complexity, maintenance (including winterizing), and likelihood of problems developing? In many cases, water-cooling, especially with a water pump, is difficult to justify, particularly if cooler air can be ducted in from elsewhere in the boat to achieve a similar result with less complexity and fewer maintenance issues.

- ***Through-hull condensers and keel coolers.*** In recent years a couple of interesting variations use no water pump for water-cooling in constant-cycling DC refrigeration units. In one variant from Isotherm, a condensing coil is installed in a through-hull. In another, from Frigoboat, a small keel cooler is added to the outside of the hull, and the refrigerant is circulated through it. In both cases, the refrigerant is taken to the water, rather than the water brought to the refrigerant with a pump.

At anchor, the boat must have some minimal rocking motion in order to constantly change the water in the through-hull version. If this does not occur, the water steadily heats up, rendering the refrigeration unit increasingly ineffective. To maximize the heat transfer in calm water, the through-hull should be set as far off the centerline as possible, while still keeping it submerged at all angles of heel. (The farther you get from the centerline, the greater the motion when the boat rocks). A keel cooler does not suffer from this problem; in most situations it provides efficiency benefits over traditional water-cooling because it eliminates the energy drain of the water pump, simplifies installation, and doesn't require the maintenance (including winterizing) associated with a water pump.. In some waters, however, a keel cooler may require scrubbing to remove biofouling. The extent to which fouling interferes with its heat-exchange properties is under investigation; the interference may not be as great as many assume.

Keel coolers must be sized for a broad range of water temperatures and optimized for typical temperatures. As a result, they have limitations in extreme conditions. In very cold water—such as may be found in Maine or the Baltic at the beginning of the boating season—there is a tendency for the refrigerant in the system to puddle out in the keel cooler, making it difficult to establish refrigerant flow at the start of the refrigeration cycle.

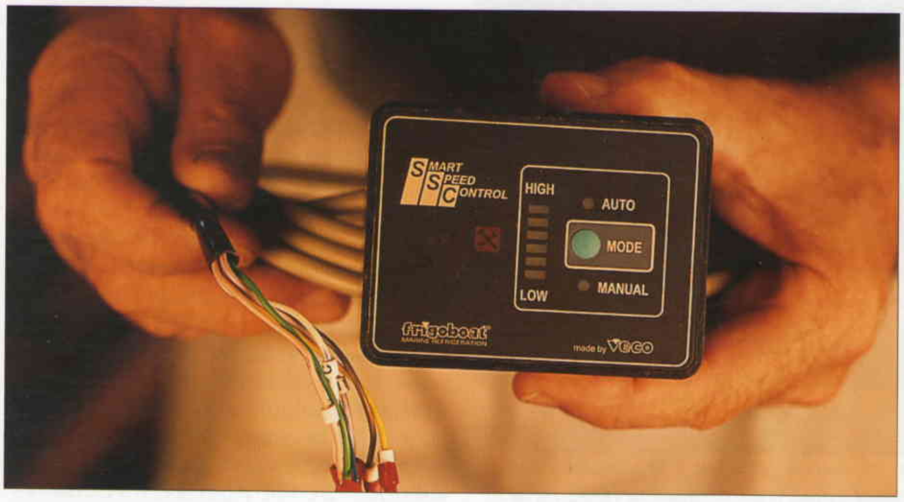
Through-hull condensers and keel coolers must be grounded to the boat's common ground point. Otherwise, any kind of DC electrical short (e.g., from a thermostat) to any of the copper tubing in the refrigeration system can put stray current into the water via the through-hull or keel cooler. The current will find its way back to battery negative through the propeller and propeller shaft, or a grounded through-hull. In the process, it will destroy the through-hull or keel cooler in short order.

Holding-Plate DC Refrigeration

Holding plates for refrigeration systems with relatively light loads can be pulled down over time by the small Danfoss compressors found in constant-cycling units (see, for example, Technautics' system, and some from Isotherm), with potential efficiency gains.

Adding holding plates, though, has its disadvantages: they increase cost and weight; they're more complex, because the holding plates require expansion valves that must be "tuned" to the system (as opposed to the capillary tubes in other small DC systems, which require no user interaction—more on these, below); and the plates take up otherwise usable space in the icebox. Holding plates do not hold as consistent a temperature in the icebox as do evaporator plates. The benefits of holding plates over an evaporator plate in small DC systems are arguable.

To take full advantage of a holding-



Frigoboat's Smart Speed Controller, like Adaptive Energy Optimization, allows the compressor to run more efficiently.

plate system, a larger compressor is needed, commonly driven by a ½-hp DC motor (see, for example, units from Glacier Bay and Sea Frost). A suitable bank of good-quality deep-cycle batteries can sustain a refrigeration load of up to ½ hp for extended periods (1 to 2 hours at a time). The current draw of the unit will be around 40 amps at 12V (20 amps at 24V) on a fully defrosted holding plate, tapering down to as little as 20 amps at the end of the freeze cycle. Such a system will handle substantial refrigeration and freezer loads—up to 10 times the small, constant-cycling units. However, it will function only if backed with a continuous DC charging source or a high-capacity DC system. (Sea Frost recommends a minimum battery bank of 660 Ah at 12V.) As noted above, the refrigeration control circuitry should include the capability to turn the unit on and "top it off" whenever the engine is cranked. This will optimize engine-running time and minimize the load on the batteries.

A large-capacity DC holding-plate system is expensive—even ignoring the cost of upgrading the DC system, should that be necessary—but it has a considerably greater refrigerating capability than any constant-cycling unit. It may also be more efficient than a constant-cycling system, or a small DC compressor coupled to holding plates. So, even though a large-capacity DC holding-plate system consumes far more power *when running,* it will provide an equivalent refrigeration capability for less *overall* power consumption, or provide a greater capability for the same overall power consumption. (Although data is available that quantifies the efficiency gains of larger compressors over smaller compressors, I know of no data that compares the likely lower efficiency of a holding plate to an evaporator plate. Consequently, I have not seen any data to quantify the overall efficiency differences between the systems.) If the DC system includes a large wind generator and/or a large-enough array of solar panels, the needs of substantial iceboxes can be met during extended cruising without having to crank the engine.

Constant-cycling DC Refrigeration vs. Holding Plate

For a decade or more, I have been an advocate of high-capacity, holding-plate, DC refrigeration rather than constant-cycling. This is because the holding-plate system has had considerably greater capacity and efficiency. I've recommended such a system to numerous people, designed them for a number of boats, and put it on my own boats. In recent years, though, technology and legal changes have altered the cost/benefit analysis on which I've based this recommendation. Here are some of the factors that have changed:

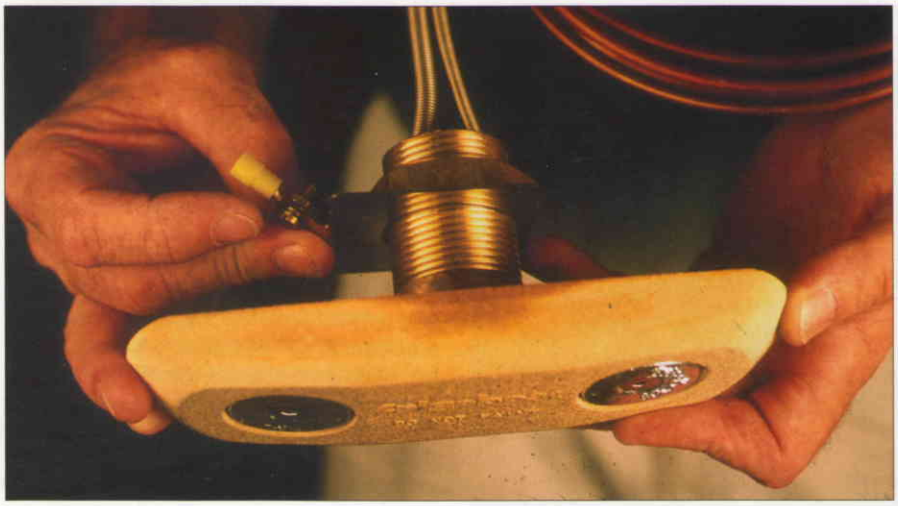
- The relative efficiency of the small compressors used in constant-cycling units versus the larger versions used in holding-plate systems has improved.
- The efficiency of the small compressors can be further boosted by a variable-speed controller such as the Smart Speed Controller from Frigoboat, or Adaptive Energy Optimization from Danfoss (see page 44). These efficiency gains are made by running compressors for longer hours at lower loads, and thus can be realized only on air-cooled units, or on those with a through-hull cooler or keel cooler—i.e., without a water pump—because if a water pump is run for longer hours, its added power drain cancels out the efficiency gains at the compressor.
- The refrigeration capability of constant-cycling compressors has increased by over 50% in recent years and, with the introduction of the new Danfoss BD80, has just gone up another 50%. In the past, the available constant-cycling refrigeration units have often been marginal in terms of their capacity to handle even midsized refrigerator and freezer iceboxes in warm climates and reliably maintain the necessary temperatures for a dependable freezer. This is no longer the case.
- Improved insulation around an icebox considerably reduces the refrigeration load, enabling this load to be met by a lower-capacity refrigeration unit. For those on a limited budget wanting to improve the efficiency of a refrigeration unit, *the same increase in efficiency can often be achieved at lower cost by upgrading the insulation than it can by investing in an expensive high-capacity holding-plate system.*

When you put these factors together, and consider that the high-capacity holding-plate DC refrigeration systems are commonly four times as expensive as a constant-cycling unit, for many boats it's difficult to justify the added cost. On the other hand:

- If superinsulation is part of the setup, it can rapidly eat up a large part of the cost savings; and
- Although they are better than they used to be, the constant-cycling units still have a limited ability to handle refrigeration loads. The upper limit for tropical cruising on a well-insulated icebox is somewhere around 15 cu ft (0.4m³) for a refrigerator and 5 cu ft (0.14m³) for a freezer. Larger iceboxes will need either some type of holding-plate system or more than one constant-cycling unit in the icebox. Another approach is to break up the refrigeration load into multiple smaller iceboxes using individual constant-cycling units.

There are spin-off benefits associated with constant-cycling refrigeration that need to be considered in making the choice between constant-cycling and holding-plate refrigeration:

- First and foremost is the maintenance issue. Constant-cycling refrigeration utilizes what are known as hermetic compressors. These are sealed inside the refrigeration unit, as opposed to the externally driven compressors that have predominated in



A Frigoboat keel cooler with grounding tab. Keel coolers eliminate the need for a water pump in constant-cycling DC refrigeration units. Frigoboat's keel cooler is attached to the outside of the hull, and the refrigerant is circulated through it.

Loaded iceboxes with holding plates (freezer on the left, refrigerator on the right) on the author's previous boat. These boxes have holding plates located at the backs of the boxes. Note the considerable volume they occupy.

high-capacity holding-plate systems, including engine-driven systems. The latter have seals that often leak refrigerant over time; the former do not. The elimination of the leaks with hermetic compressors becomes ever more important as the legal framework within which refrigeration units are operated is tightened—especially in Europe—increasing the cost and difficulty of servicing units. (Note that all AC systems, including constant-cycling and holding-plate, also have hermetic compressors, as does the Glacier Bay Micro HPS system; see below.)

- Most of the constant-cycling units employ what is known as a capillary tube to dispense the refrigerant. A capillary tube has no moving parts, in contrast to the expansion valves used in holding-plate systems, which not only have a number of moving parts but also require considerable expertise to set up and adjust properly. In general, as long as it is installed properly, you can pretty much fit and forget a constant-cycling unit (much as with a household refrigerator), whereas the high-capacity holding-plate units require some maintenance and are more prone to trouble. In the event the system fails and needs replacing, the constant-cycling unit will be cheaper and easier to replace. Capillary tubes are less efficient than expansion valves, but on the low-capacity constant-cycling units the difference is not that significant.
- Constant-cycling refrigeration eliminates holding plates and replaces them with a thin evaporator plate or box, the same as the evaporator plate or box in a household refrigerator. This frees up a fair amount of volume in the icebox. Between the weight savings on the refrigeration unit itself and on the holding plates, a considerable amount of weight can be gotten out of the system—generally, at least 100 lbs (45.4 kg). When a unit is first turned on, an evaporator plate pulls down much faster than a holding plate, and maintains a more consistent icebox temperature than most holding plates.
- Because constant-cycling units have a relatively low-capacity compressor, the demands on the cooling system (the condenser, an essential component in the refrigeration process) are considerably less than the demands of the high-capacity DC systems. As noted above, this lower demand can be met by an adequately sized air-cooled condenser or a small keel cooler installed on the outside of the hull, removing the need for a water-cooling circuit, together with its pump and associated energy drain and maintenance.

Hybrids

If the story ended here, it would make a pretty strong argument for constant-cycling DC units in many applications where holding-plate refrigeration would have previously been a better choice. But the simple lines I have drawn are blurred by recently introduced "hybrid" systems such as Glacier Bay's Micro HPS (the letters stand for "holding-plate system").

The Micro HPS is a high-capacity system that uses a powerful new hermetic DC compressor, eliminating the maintenance associated with externally driven compressors. The electrical windings in hermetic compressors are generally cooled by the refrigerant gases on the suction side, adding the heat of the windings to the work the compressor has to do. The Masterflux compressor in the Micro HPS uses the discharge gas from the compressor for cooling the windings, adding this heat to the condenser's load rather than to the compressor's load. The net effect is an improvement in efficiency over a conventional hermetic compressor.

The Micro HPS system comes in a compact, precharged, skid-mounted configuration that simply needs the refrigerant and cooling lines to be con-

Source List for Products Mentioned in the Text

Danfoss Inc.
7941 Corporate Dr.
Baltimore, MD 21236 USA
tel. 410–931–8250
fax 410–931–8256

Frigoboat
(VECO N.A., international distributor)
P.O. Box 3518
Annapolis, MD 21403 USA
tel. 301–352–6962
fax 301–352–5739
www.frigoboat.com

Glacier Bay Inc.
2845 Chapman St.
Oakland, CA. 94601 USA
tel. 510–437–9100
fax 510–437–9200
www.glacierbay.com

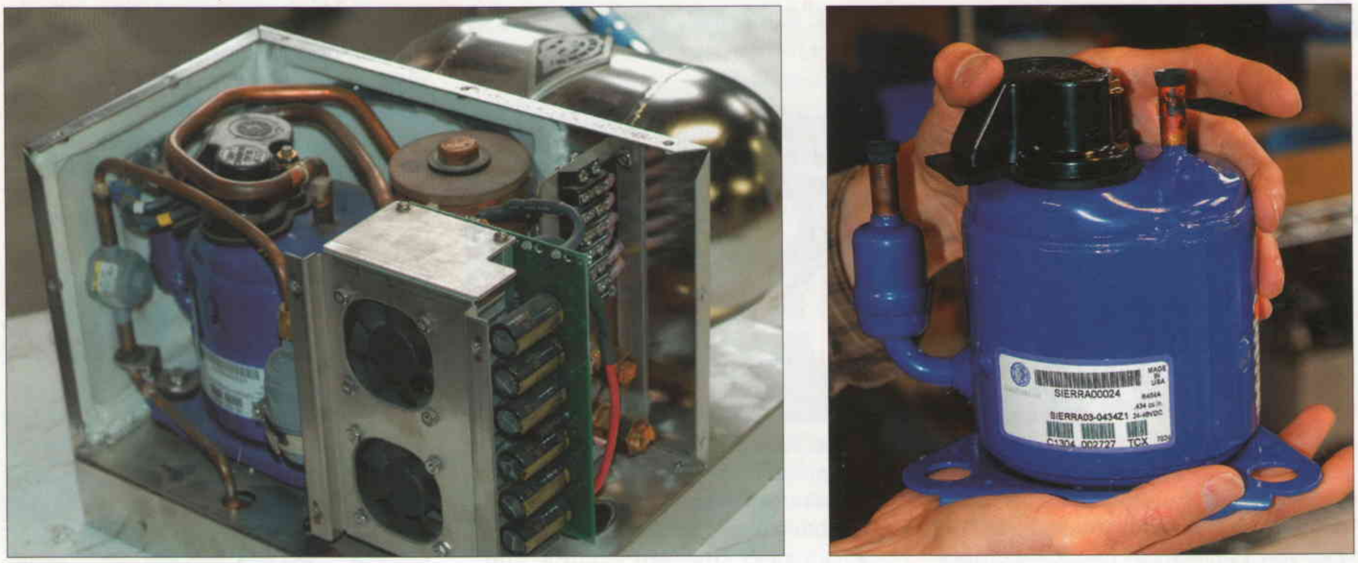
Isotherm
Indel Marine
I-61019 S.Agata Feltria (PS) Italy
tel. +39 0541 848030
fax +39 0541 848563
www.isotherm.com

Norcold
P.O. Box 180
600 South Kuther Rd.
Sidney, OH 45365 USA
tel. 800–543–1219
fax 937–497–3092
www.norcold.com

Sea Frost
372 Route 4
Barrington, NH 03825 USA
tel. 603–868–5720 or 800-435-6708
fax 603–868–1040
www.seafrost.com

Technautics Inc.
1760 Monrovia Ave., Ste. A-2
Costa Mesa, CA 92627 USA
tel. 949–645–3861 or 800–568–8979
fax 949–645–3230
www.technauticsinc.com

WAECO USA Inc.
8 Heritage Park Rd.
Clinton, CT 06413 USA
tel. 860–664–4911
fax 860–664–4912
www.waeco.com
and www.waecousa.com



Left—*Glacier Bay's Micro HPS system. The vertical unit with the fans and capacitors on the side is an electronic commutator for the brushless DC permanent-magnet motors used in the compressors.* ***Right***—*Glacier Bay's "Masterflux" hermetically sealed DC compressor, part of the HPS system, offers outputs up to 2 hp.*

nected. In other words, installation is no more complicated than that for many constant-cycling units—although it still needs to be vacuumed down, as opposed to a number of constant-cycling units that do not need vacuuming. It has downsized holding plates that are between the size of an evaporator plate and a traditional holding plate, thus reducing the volume and weight of the holding plates. The net result is something midway between a constant-cycling unit and a traditional holding-plate unit, which is reported to have a higher efficiency than a constant-cycling unit; up to 10 times the refrigerating capability (as long as the holding plates have the capacity to absorb this capability); and less potential for leaks than a traditional holding-plate system equipped with an externally driven compressor. If the emphasis is on capacity and efficiency, then the refrigeration load may best be met with a hybrid system, although it will take a few years to assess the cost-effectiveness of this approach, as well as its position in the marketplace.

Another interesting product that has been around for a while without gaining much traction in the marketplace is Glacier Bay's Micro Blast Chiller. The most recent variant has a refrigeration unit that uses a Masterflux compressor with propane as a refrigerant. It comes as a complete setup in which the evaporator is part of the unit instead of being installed in the refrigerator. A fan blows air over the evaporator, dropping the air temperature to well below freezing. This air is then ducted into the icebox to refrigerate the contents.

Making Choices

Where refrigeration loads are relatively light, and in situations where a boat is used primarily on weekends and plugged into shoreside power during the week, constant-cycling DC refrigeration is by far the most economical, troublefree, and easy to install for most boats.

If greater capacity is required, then engine-driven refrigeration makes sense in situations where engines are run regularly; the DC system is somewhat weak; and refrigeration is not required at dockside. These are the conditions found on many charter boats.

If an AC generator is constantly running, household constant-cycling equipment will be the most economical. If an AC generator is intermittently, but regularly, operated, AC holding-plate refrigeration makes sense.

In most other situations, some variant of DC refrigeration is the best choice, because it can:

- Minimize engine-running hours;
- Be operated from shore power via a battery charger (whereas an engine-driven system requires the engine to be run at dockside); and
- Be left to run at anchor until the batteries go dead. (One of the design parameters I set myself is a battery and refrigeration balance that will allow the boat to be left unattended for up to a week without the fridge and freezer melting down.) In contrast, engine-driven refrigeration requires someone to be on the boat to run the refrigeration unit every day.

With respect to the DC options, I believe the balance of the argument has shifted in favor of constant-cycling DC refrigeration, even on a hard-core cruising boat, although the jury is still out on the hybrid systems. Better yet is to have two (or more) units—separate fridge and freezer installations—to provide built-in redundancy. There will still be cost savings over a high-capacity holding-plate DC system, some of which can be put into improved insulation. The end result will be a virtually maintenance-free refrigeration system that is compact, quiet, and reliable; that optimizes the icebox volume and keeps down weight; that has built-in redundancy; and all at a cost that is less than that of a high-capacity holding-plate system. PBB

About the Author: *Nigel Calder, author of* Boatowner's Mechanical and Electrical Manual *and other marine titles, is a contributing editor of* Professional BoatBuilder *and a member of the ABYC's Electrical Project Technical Committee.*

Reprinted with permission from PROFESSSIONAL BOATBUILDER MAGAZINE, October/November 2004