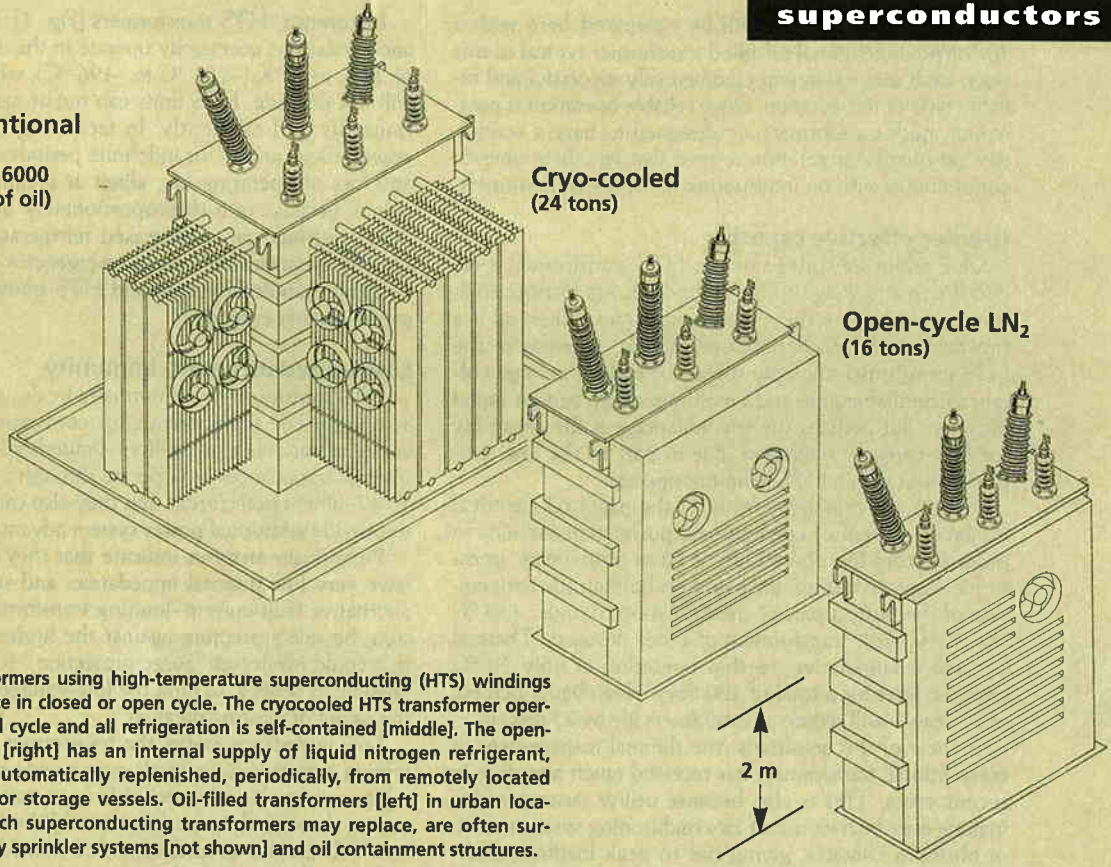


18

Conventional
(48 tons;
includes 6000
gallons of oil)

Cryo-cooled
(24 tons)

Open-cycle LN₂
(16 tons)



[1] Transformers using high-temperature superconducting (HTS) windings can operate in closed or open cycle. The cryo-cooled HTS transformer operates closed cycle and all refrigeration is self-contained [middle]. The open-cycle unit [right] has an internal supply of liquid nitrogen refrigerant, which is automatically replenished, periodically, from remotely located liquefiers or storage vessels. Oil-filled transformers [left] in urban locations, which superconducting transformers may replace, are often surrounded by sprinkler systems [not shown] and oil containment structures.

Waukesha Electric Systems

Transforming transformers

Use of high-temperature superconducting windings may soon turn power transformers into compact high-performers on good terms with the environment

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Transformers utilizing high-temperature superconductors are viewed as a "breakthrough" technology coming at a very "opportune time." Possible utility customers for the new equipment, as well as power transmission and distribution experts, have gone on record with this judgment [see "The need and the promise," p. 47].

High-temperature superconductor (HTS) properties, improved refrigeration reliability, and lower refrigeration costs make it possible to overcome the limitations experienced in the low-temperature superconductor (LTS) transformer designs of the 1970s and '80s. (Note that HTS and LTS are relative terms for superconductors operating more than 195 degrees below 0° C.)

Commercial success will depend on demonstrated reliability of operation and the scale-up of (HTS) manufacturing. The goal is to reach the high current densities already obtained in short conductor samples, except in long lengths and at reasonable cost. Such rapid progress is being made that commercially competitive and operationally superior HTS transformers are expected to be available in five to 10 years.

The potential for HTS transformers is being examined in major design and hardware development programs by several teams of engineers and scientists worldwide. The team to which the authors belong is led by Waukesha Electric Systems, in Wisconsin, and has three New York members—Intermagnetics General Corp., Rochester Gas & Electric Corp., and Rensselaer Polytechnic Institute—plus Oak Ridge National Laboratory, in Tennessee.

The Waukesha-led team has conducted a series of reference designs concentrating mostly on a 30-MVA, 138-kV/13.8-kV transformer rating. This rating is representative of a medium-power transformer class foreseen as comprising about half of all U.S. power transformer sales in the next two decades.

Two of these designs will be compared here with a 30-MVA conventional oil-filled transformer typical of this class. Each uses a different commercially successful and reliable type of refrigeration. Since reliable operation is paramount, both transformers are designed to have a several-day, on-board refrigeration reserve that lets them operate continuously with no interruption of service to customers.

Greater effective capacity

One major advantage of the HTS transformer is reduced size and weight [Fig. 1]. Another is a distinct environmental plus—in the conventional transformer, oil is a fire hazard and potential contaminant, whereas in the HTS transformer, the only substance present in large volume is nonflammable and environmentally benign liquid nitrogen. But perhaps the key advantage is the capability for over-capacity operation, due in part to the low temperatures at which HTS windings operate.

Heat is the principal enemy of the paper-oil electrical insulation system of conventional power transformers. In order to meet the desired life of 30 or more years, transformer capacity ratings are based on holding the temperature of the hottest part of the insulation to under 110 °C (or 95 °C with transformers of older designs). Thermal damage is cumulative, so that operation at only 20 °C over the limit for a total of 100 days—less than 1 percent of 30 years—will reduce a transformer's life by 25 percent.

In view of this sensitivity, the thermal management of conventional transformers has received much attention in recent years. This is also because utility customers are making ever heavier use of air-conditioning systems, even in northern climates, giving rise to peak loading conditions that can last 10 hours or more on the hottest days of the year. Loss of insulation life can be significant under these conditions. So transformers are increasingly being purchased with excess capacity, just to meet maximum temperature limits that may occur only on a few days. The upshot is that they operate well below an optimal level most of the time.

Defining terms

Cryocooler: a refrigerator designed to operate in the range of low temperatures where common gases become liquid or solid. A Gifford McMahon cryocooler is one of several types that operate through an oscillating gas pressure used to carry heat away from a bed of material.

Eddy current losses: loss of energy as heat, caused by local currents induced in the superconductor or other metallic components by changing magnetic fields.

Liquefier: a refrigerator that cools gases until they condense into liquids; in some cases, the cooling is effected by the expansion of the gas itself.

Magnetic hysteresis losses: in ferromagnetic materials, the loss of energy as heat caused by a lag and irreversibility in the alignment of magnetic domains with respect to a changing magnetic field.

Resistive losses: loss of energy as heat caused by the passage of a current through material having electrical resistance. In a conventional 30-MVA transformer, this may constitute 60 percent of the transformer loss at rated load.

Superconductor hysteresis losses: loss of energy as heat, the cause being an irreversible penetration of a magnetic field into a superconductor because persistent superconducting currents are induced.

Total owning costs: the transformer's initial purchase price plus the effective cost of load-cycle-dependent losses.

In contrast, HTS transformers [Fig. 2], their windings, and insulations necessarily operate in the ultra-cold range of 20 K to 77 K (−253 °C to −196 °C), where insulations will not degrade. HTS units can run at rated power continuously and efficiently. In fact, at up to twice rated power, they can run for indefinite periods of time without any loss of operating life, albeit at greatly reduced efficiency because of a disproportionately increased use of liquid nitrogen or an increased refrigeration load. Thus one HTS transformer can in emergencies carry the loads normally handled by two, and HTS transformer lifetime can be greatly extended.

Low impedance with immunity

HTS transformers will normally be designed to operate as one-for-one replacements for conventional transformers, complete with an ability—limited only by their own internal impedance—to operate through a fault current of 10-12-times rated current. But they also can be configured to provide additional power system advantages.

Preliminary analyses indicate that they can be built to have very low internal impedances and still, through an alternative fault-current-limiting transformer winding design, be self-protecting against the higher fault currents that could result [see "Surge protection," p. 26]. It may be possible, if needed, to limit the low-voltage side current to the rating of existing breakers.

Low impedance makes the transformer better at maintaining output voltage levels over a wide range of operating power levels and better able to transmit power downstream through the power system. Utilization of this feature will involve consideration of transformer interfaces with the grid and the load in each situation, and may especially apply to new power construction where a complete system of compatible components can be installed in an economical way.

Conventional transformers are efficient (typically 99.3–99.7 percent for the 30-MVA class, depending upon loading); but there is considerable room for improvement. About 25 percent of the 7–10 percent losses in transmission and distribution systems occur in power transformers. The transformer loss costs more than \$2 billion annually in United States alone.

Most of the conventional transformer's losses are due to resistive heating in its windings—and HTS transformers have zero winding resistance. Admittedly, the HTS versions still have ac losses in the iron core and low levels of other kinds of ac losses in the windings that require refrigeration power. Nonetheless, they can be substantially higher in efficiency than conventional transformers, to the extent that the reduced loss in each HTS unit can more than pay for its initial capital cost over its lifetime.

Design tradeoffs, cost drivers

Zero resistance and 10-100-times greater current density promise striking advantages in transformer size and performance. Classical resistive losses are eliminated, and the quantity of conductor in the HTS transformer windings can be reduced to tens as against thousands of kilograms for the conventional transformer. Since the windings in principle require little space and generate little resistive heat, it should be possible to make superconducting transformers inexpensively, with greatly reduced power capacity, much increased efficiency, and very much smaller size. While these advantages can be realized in large part, they cannot all be achieved to the same degree in the same transformer. As always, there are practical limitations and tradeoffs.

Ultimately, reductions in size will be limited by dielec-

tric design considerations. The transformer must meet American National Standards Institute standard dielectric tests for system voltages and the associated basic impulse insulation test levels that are specified. For example, a 138-kV winding may need to withstand impulse voltages of 650 kV. The design of the transformer winding must include sufficient space for insulation if it is to accommodate these high voltages with commercially available dielectric materials and proven design approaches.

Iron core size, which is related to winding size, mainly determines overall transformer size and weight. Eddy current and magnetic hysteresis losses are produced in the core in direct proportion to the core volume. These losses tend to be on the order of tens of kilowatts, much too large to be

economically removed by low-temperature refrigerators. HTS transformers are consequently designed to operate with cores near ambient temperature and isolated thermally from the windings. If the core is too large, its losses become excessive, and because these losses occur regardless of whether current (power) is drawn from the transformer, they contribute strongly to the total owning costs. So there are strong incentives to reduce core and winding size.

But reducing core diameter adds to the number of turns and so to the total length and cost of the HTS conductor. Though the superconductor winding has no classical resistive losses, there are several forms of eddy current and hysteresis losses, which depend on the magnitude of the ac magnetic flux density in the transformer windings, typi-

The lengths (and more) to which HTS must go

Continuous lengths of several hundred meters of high-temperature superconductor (HTS) are required for the construction of transformer windings. While many HTS families are known, the manufacture of long lengths is being developed in only a few of them.

The farthest along are several variations of the BiSrCaCuO family, with the numbers of atoms in the cations in the ratios of either 2212 or 2223. The BSCCO-2223 is currently manufactured in flat tapes up to 1 km long; fine filaments of the oxide superconductor are encased in a silver or silver alloy matrix by a powder-in-tube (PIT) draw, roll, sinter, and roll process. The BSCCO-2212 is currently being manufactured in wires or tapes up to 0.5 km long by either a PIT or a surface-coating process. The final step in either case is a melt and resolidification of the oxide.

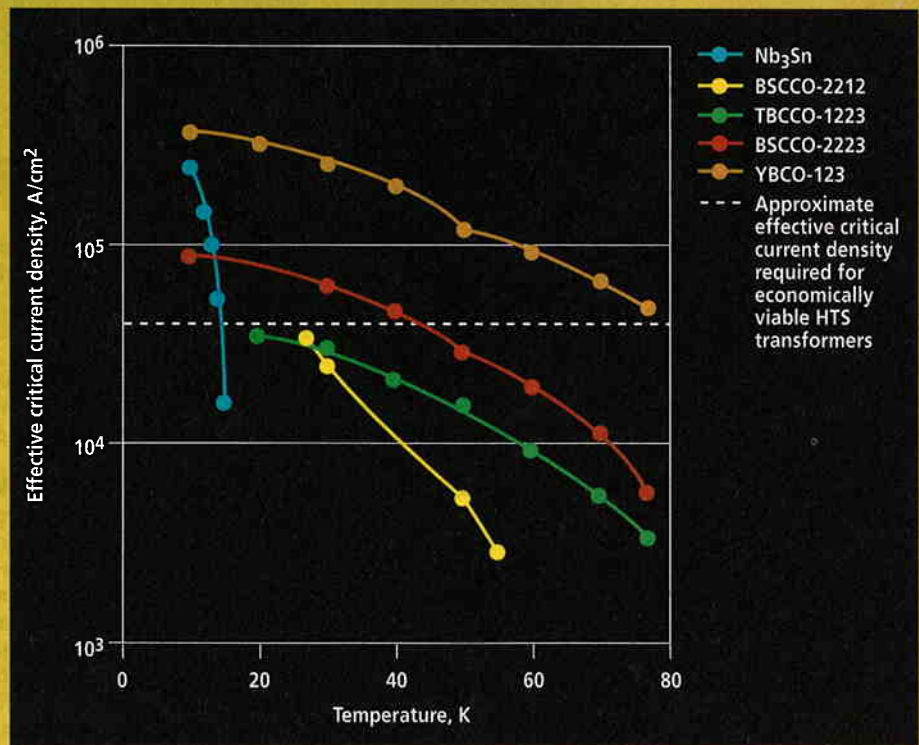
TiBaCaCuO (TBCCO-1223) and YBaCuO (YBCO-123) have been made by various surface-coating or surface deposition processes, but have proved harder to produce in length in suitable form. Recent breakthroughs in producing YBCO with very high critical-current densities on nickel and nickel-based alloy substrates are beginning to change the picture. An avalanche of development activity worldwide covers a range of manufacturing approaches. High-quality conductor is being produced in 10-cm lengths, and apparatus is being scaled up to make longer lengths [see pp. 18–19].

In the figure, the best critical-current densities in short samples of these conductors (that is, the peak zero-resistance current per unit of oxide cross section) are combined with the authors' estimates of achievable substrate-to-oxide ratios in order to estimate achievable engineering critical current densities (current per unit of total conductor cross section). Assume for reference that each of these superconduc-

tors will be manufacturable in long lengths at a target cost of about \$1000/kg—that is, for about the present cost of multifilamentary Nb₃Sn, the more expensive of the low-temperature superconductors. If so, an engineering critical-current density of at least 40 000 A/cm² will be needed to economically provide the ampere-turns of conductor required for HTS transformer applications.

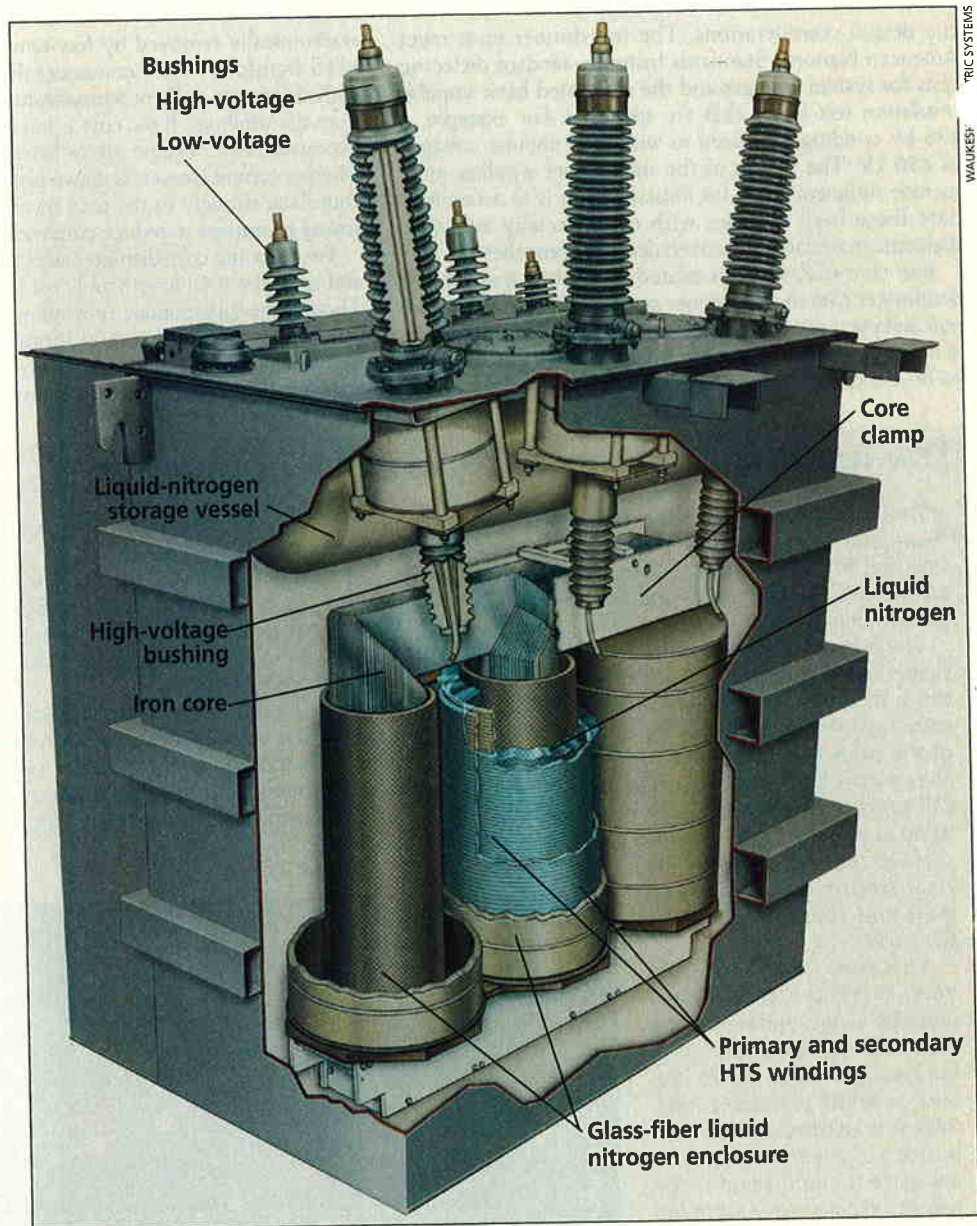
This line of reasoning establishes a temperature range for the economical use of each of these conductor types in these applications. If conductor properties are improved, or if the manufacturing cost is lowered, then the practical range for each conductor type will shift to higher temperatures.

—S. P. M., N. A., & M. S. W.



HTS transformers need a certain critical-current density for viability [dashed line]. The target levels shown for four high- and one low-temperature superconductor are based on test results for short samples and estimates of achievable substrate-to-oxide ratios. The BSCCO-2212 results are for dipcoat tape from Japan's National Research Institute for Metals and powder-in-tube (PIT) wire from Intermagnetics General, which also produced BSCCO-2223 in multifilament PIT tape form. The TBCCO is for spray-pyro tape made by General Electric, while the YBCO-123 tapes were produced by new techniques at the Los Alamos and Oak Ridge national laboratories. The low-temperature Nb₃Sn is multifilamentary.

[2] This artist's conception of a superconducting transformer resembles conceptually the one being developed by Intermagnetics General and Waukesha Electric. Note in particular the location of the liquid-nitrogen storage vessel, inside the top of the transformer box, and the enclosure containing liquid nitrogen around the primary and secondary superconducting windings.



cally a maximum of 0.1–0.3 teslas. Compared to conventional resistive and eddy current losses, ac losses in the HTS transformer winding are small, but because they occur at low temperatures, it takes many times their value in refrigeration power to extract the heat produced. The multiplier is 20 at 77 K, increasing to over 100 at 20 K.

Great care is therefore given to the design of low-loss conductor and winding configurations. At a fixed transformer power rating, the ac flux density in the windings is increased as the size of the transformer core (and windings) is reduced. Dielectric ac losses in insulating materials also tend to increase as the volume of the winding is reduced. HTS transformer designs are therefore made with the core large enough so that conductor quantity and cost are reasonably low and the fields on the windings are low enough to keep ac losses within reasonable limits.

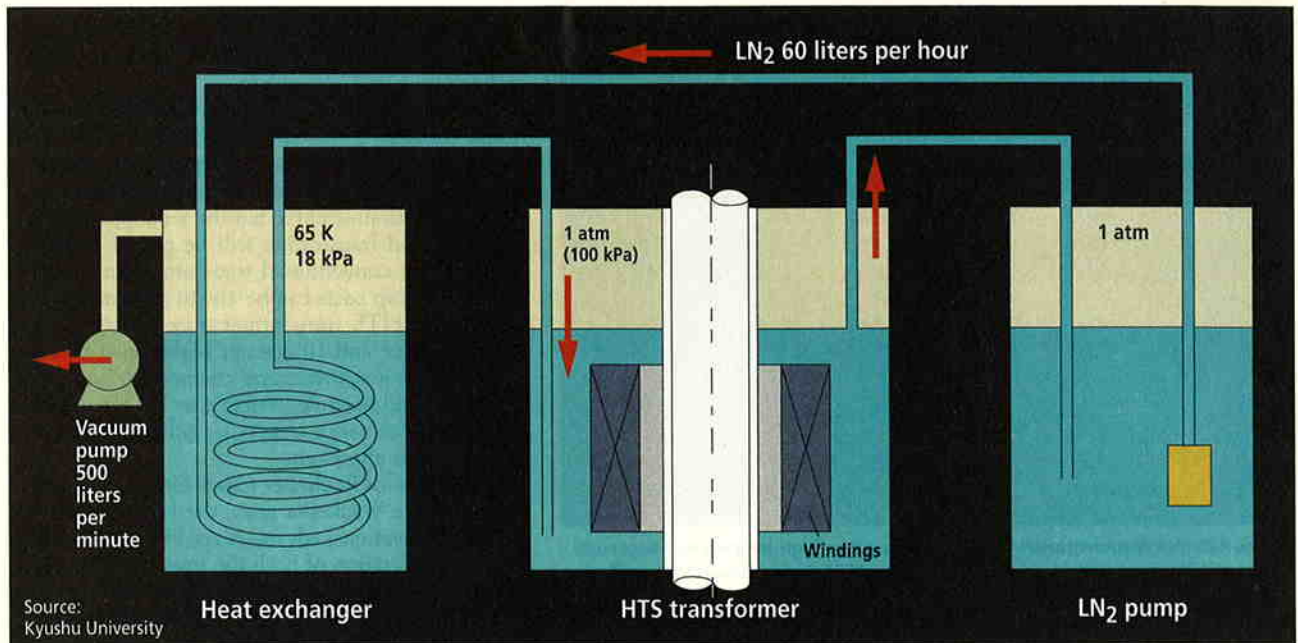
Another tradeoff involves the current density of superconductors, which increases as their operating temperature is decreased ["The lengths to which HTS must go," p. 45]. Clearly, the lower the operating temperature, the less superconductor material is needed to provide the ampere-turns of the transformer windings, and the lower its cost becomes. But, as noted earlier, the lower the oper-

ating temperature, the higher are both refrigeration capital costs and the refrigeration power needed to remove the ac losses that are generated.

How to cool and keep cool

One of the preferred approaches to cooling and electrically insulating the windings is to surround them with liquid nitrogen (LN_2), which is the only safe and low-cost cryogen available in liquid form in the 20–77-K temperature range of interest. It is an excellent electrical insulator and low-loss dielectric, provided that gas bubbles are not allowed to form. The tendency for gas to bubble is suppressed by sub-cooling the liquid nitrogen below its boiling point (77 K at one atmosphere pressure) to as low as 63 K, whereupon it solidifies. This can be done by passing the liquid at one atmosphere pressure through a bath of the same stuff boiling at reduced pressure and temperature [Fig. 3].

The nitrogen can be either refrigerated and re-condensed within the transformer, in a closed cycle, or allowed to boil away, in open cycle. In the second case, it serves as a portable, storable refrigerant that absorbs 44 Wh of heat per liquid liter. In this mode it needs replenishment by periodic transfer of the liquid element through thermally insu-



[3] The cryogenic system for an experimental 500-kVA transformer using high-temperature superconductor windings was built and successfully tested by the Japanese team made up of Kyushu University, Fuji Electric, and Sumitomo Electric Industries.

lated pipes from remote storage vessels. The vessels can be refilled from on-site liquefiers, but a least-cost approach (\$0.08 per liquid liter) is to have liquid nitrogen delivered as needed several times per year from large efficient liquefaction plants. Such deliveries to hospitals and industrial concerns are highly reliable and common throughout the United States and much of the industrialized world. Since transformer losses cooled by liquid nitrogen may be hundreds of watts, cooling costs by this approach can be on the order of \$1/h.

Cryocoolers can also serve to directly cool the HTS windings. Their use allows the operating temperature of the windings to be selected at optimal levels without restriction of the liquid nitrogen range. On the other hand, electrically insulating the windings and providing a refrigeration reserve becomes more challenging with this approach.

A preferred thermal insulation between ambient and

cryogenic environments is vacuum. Evacuated metallic double-walled vessels (dewars) are routinely used for the storage and transportation of cryogenic liquids. No active pumping of the vacuum spaces is required over years of operation. To prevent heating due to induced current, vacuum-tight nonmetallic vessels will be required to contain the liquid nitrogen surrounding the transformer windings.

Regardless of the general thermal insulation approach, heat from the warm outside world and heat generated in the electrical leads will be conducted down the leads to the winding area. This adds both fixed and load-dependent components that may account for half or more of the refrigeration load of the transformer. The economics of refrigeration on a cost-per-unit power basis thus becomes more favorable for designs of higher voltage (lower current) and higher power rating.

The need and the promise

Potential users see solutions to transformer capacity problems. To quote Ronald C. Johnson and Robert H. Jones, substations engineer and senior engineer, respectively, Rochester [N.Y.] Gas & Electric Corp.: "HTS [high temperature superconductor] transformers are attractive...because they are much smaller, have greatly extended overload capability and don't have fire and environment problems associated with insulating oil.

"Our typical substation is designed with two transformers. If one transformer fails, the other is sized to carry the load of both during the emergency. An HTS transformer can carry up to 200 percent of nameplate rating indefinitely without loss of life. This means we can buy transformers of lower rating to do the same job or pack up to four times the capacity onto the same footprint area. HTS is a breakthrough technology that promises to bring sweeping changes to transformers comparable to the replacement of oil circuit breakers with breakers that use either vacuum or sulfur hexafluoride."

From a national economic and technological perspective,

the time is ripe, say two Oak Ridge National Laboratory engineers. According to Benjamin W. McConnell, senior staff, transmissions and distribution group, and James Van Coevering, power system technology program manager: "Oil-filled power transformers are a mature technology that developed gradually over the last century [and] is at its limits. Typical transformer life times are about 40 years, and the last major expansion in power capacity was about 30 years ago.

"The U.S. power industry thus has an aging inventory of oil-filled power transformers that will produce a surge of replacement demand in the next two decades. This is in addition to the need for expanded capacity, worldwide. Recent advances in HTS development make possible a superior, cost-competitive HTS transformer technology. This is an opportune time to begin to replace our aging inventory with reliable HTS transformers that are safer, operationally superior, more environment-friendly and higher in efficiency for longer lifetime operation into the next millennium." —S. P. M., N. A., & M. S. W.



ABB ASEA BROWN BOVERI

[4] The 630-kVA demonstration transformer based on high-temperature superconductor windings is presently under test by ABB, ASEA Brown Boveri Ltd., on the grid in Geneva, Switzerland. Designed to convert power from 18.7 kV to 420 V, its superconducting windings are made of power-in-tube BSCCO-2223.

Transformer costs

The convenience of liquid nitrogen as an electrical insulation, thermal reservoir, and coolant is very attractive. And the best conductor type for commercial use with liquid nitrogen, in the team's opinion, will eventually prove to be YBCO, because of its high critical current density at higher temperatures. Thus, the 30-MVA HTS transformer reference designs presented here assume this superconductor operating immersed in liquid nitrogen and subcooled to 68 K—even though YBCO has until now been made in short lengths only.

For a fair comparison with conventional transformers, it has been assumed that mature manufacturing of HTS transformers 5–10 years from now will be at the level of 100 or more units per year. Total owning costs have been calculated on the basis of two formulas: one employed by Waukesha Electric Systems for its customers, and one from the U.S. Department of Energy that puts more emphasis on loss-connected costs. Comparative costs are reported here in ranges that reflect the use of these formulae and some of other uncertainties.

To reduce uncertainties over the projection of conductor costs, these transformer designs minimize the quantity of superconductor to 30–45 kg and so limit its cost. Thus, at a target superconductor price of \$1000/kg, the cost of superconductor is 10–15 percent of the total cost of the transformer. As already noted, however, reducing the quantity of superconductor requires enlarging the cores and hence core losses, so total owning costs may be relatively higher than with HTS transformers more optimally designed for total owning costs.

The open-cycle, liquid-nitrogen-cooled HTS transformer has been designed to substitute directly for a conventional transformer. Its internal impedance is typical of conventional transformers, and its winding will remain superconducting through the maximum fault current allowed by its impedance. Costs for this transformer include liquid nitrogen storage and delivery. The cryo-cooled HTS transformer can also be designed for direct substitution, but by way of illustration here, the Waukesha-led team chose instead a passively self-protecting design much lower in impedance. Recognizing the intermediate stage of refrigerator development, it also has been designed for relatively low ac losses and refrigera-

tion loads. It is larger than the open-cycle, liquid-nitrogen-cooled transformer, in part to accommodate enclosed on-board refrigeration.

The present price of a baseline 30-MVA conventional transformer is around US \$300 000. Total owning costs for this transformer range from about \$400 000 to \$500 000. Standard formulas are somewhat biased against HTS, but the team projects that an LN-cooled transformer will be priced comparably with the conventional transformer and that its total ownership costs can be 10–20 percent lower. A cryo-cooled HTS transformer may be 30 percent higher in price and 10 percent higher in total owning cost than its conventional counterpart. Lower-cost versions should become available as HTS conductor cost and performance targets are achieved and refrigeration costs improved.

In the view of Rochester Gas & Electric, the utility partner in the Waukesha team, the lower installation costs and operational advantages of HTS transformers justify consideration of both the open-cycle and cryo-cooled systems described. The economics become even more favorable for HTS transformers of higher rating. ABB Asea Brown Boveri Ltd., Zurich, Switzerland, has performed conceptual studies that suggest a more than 20 percent reduction in capital cost, more than 50 percent reduction in weight, and nearly 70 percent reduction in losses for 100-MVA transformers utilizing HTS, as compared to conventional transformers.

Development program doings

Teams in Japan and Europe are beginning to develop the technology and test the operation of liquid-nitrogen-cooled transformers using BSCCO-2223, at present the best of the conductors being made in long lengths for operation above 63 K. With further improvements in its properties and with sufficient cost reductions, BSCCO-2223 may yet produce economically viable HTS transformers to operate in this temperature range.

The same transformer cooling approaches being developed can serve for YBCO. The Waukesha-led team has chosen direct cooling with cryocoolers because this approach allows economic use of the best available HTS conductor at a temperature optimal for the combination of conductor performance, cost, and refrigeration.

In Japan, Kyushu University, Fuji Electric, and Sumitomo Electric Industries reported in August 1996 on a sub-cooled liquid-nitrogen-cooling approach along with a unique, low-ac-loss winding transposition scheme. For their successful demonstration, they used a laboratory-type 500-kVA, 6.6-kV/3.3-kV transformer made from BSCCO-2223 powder-in-tube conductors operating in liquid nitrogen [Fig. 3].

Except for being single phase, this transformer is similar in construction to the transformer pictured in Fig. 4. A warm iron core extends through a hollow glass-fiber-epoxy cylindrical enclosure housing the primary and secondary windings and liquid nitrogen coolant. An efficiency of 99.1 percent was achieved with liquid nitrogen at 77 K and the transformer under load at 503 kVA. The percentage includes core losses and an equivalent refrigeration power for both ac losses generated in the windings and heat leakage into the system. Efficiencies of 99.3 percent were obtained operating in subcooled liquid nitrogen at 66 K with the transformer shorted and drawing currents corresponding to an 800-kVA loading. These results basically confirm the effectiveness of the low-loss winding scheme and the overall cooling approach.

In Europe, ABB Asea Brown Boveri, American Super-