World's first solid insulation distribution transformer

An innovative Solid Insulation Distribution Transformer (SIDT) developed jointly by ABB and Hydro-Québec, Canada, enables electric utilities to operate their power distribution systems economically while meeting strict environmental standards. SIDTs are corrosion-free, silent, withstand severe weather and contain no flammable or volatile liquids. Since they eliminate the risk of soil or groundwater contamination, SIDTs are an ideal solution for underground systems. Units with a full-load rating of 167 kVA have been successfully tested in service in Hydro-Québec's underground network since March 1996.

For years, many electrical utilities have been distributing power via underground systems. The undeniable popularity of this option is highlighted by the fact that a growing number of utilities are now considering burying all or part of their existing power systems. Unfortunately, over the years underground distribution equipment corrodes fairly quickly, and this deterioration causes a wide range of problems. One of the most serious consequences is undoubtedly the risk of leakage of the dielectric oil contained in conventional distribution transformers and other equipment. In addition to causing the eventual breakdown of the transformer, these leaks can lead to fires and violent explosions. Another significant impact is the risk of soil and groundwater contamination.

Through a joint venture known as the *Centre d'innovation du transport d'énergie du Québec*, ABB in Canada and its partner Hydro-Québec have developed a Solid Insulation Distribution Transformer (see box), also known as the 'SIDT' or 'Green Transformer', to prevent problems such as these.

An ABB market analysis has pointed to a high commercial potential for the Solid Insulation Distribution Transformer. ABB and Hydro-Québec have signed a partnership agreement, under which ABB supplies Hydro-Québec with SIDTs and the partners work to develop and market SIDT technology.

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Three SIDT prototypes (*Table 1*) have been in service with Hydro-Québec since March 8, 1996 **1**.

Unique design

The unique design of the SIDT features four fully integrated components **2**: a solid insulation system, a composite-material outer shell, a simple but highly efficient internal cooling system and magnetic-core cushioning. The ingenious combination of these four components makes ABB's Solid Insulation Distribution Transformer the ideal choice from both the engineering and environmental viewpoints.

What is CITEQ?

CITEQ stands for *Centre d'innovation sur le transport d'énergie du Québec* (Quebec power transmission innovation centre). A joint venture between Hydro-Québec and ABB, CITEQ focuses on research and development in the area of new electrical power transmission and distribution equipment.

CITEQ is strategically located at Varennes, close to ABB's power transformer plant and the Institut de recherche en électricité du Québec IREQ (Quebec electricity research institute).

The synergy generated by this profitable partnership between ABB and Hydro-Québec benefits both customers and suppliers.

On June 17, 1997, CITEQ transferred the manufacturing and marketing rights for the new transformer technology to ABB. In the first phase of the SIDT project, a pilot plant is providing data that will improve the manufacturing process, reduce material costs and standardize engineering solutions. A second phase will focus on mass production.

First series of Solid Insulation Distribution Transformers installed in a Hydro-Québec underground vault **1**

Solid insulation

The electrical insulation system is made of 100 % solid materials and requires no conventional liquid or gas dielectric medium. It is comprised essentially of insulating paper and epoxy resin. The epoxy resin, which acts as a dielectric medium, totally permeates and coats the windings and magnetic core. During the manufacturing process, the resin is poured into the transformer shell, which serves as a mould.

Composite material shell

The outer shell of the SIDT is made of a composite of fiberglass, carbon fiber and epoxy resin. It is totally waterproof and corrosion resistant and requires zero maintenance. It also reinforces the structure of the transformer.

Core cushioning

During the polymerization phase, the epoxy resin shrinks, producing mechanical forces that act on the magnetic core. This results in a significant increase in no-load losses. Magnetic-core cushioning has been developed to counteract this effect. The cushioning also compensates for the negative impact of core expansion and contraction due to major temperature changes, and considerably reduces the level of transformer noise, thus helping to create a better environment.

New cooling system

A new cooling system based on heat pipes controls the transformer's internal temperature. The heat pipes consist of an evaporator and a condenser **3**, both of which are totally passive, require no outside power supply and pose no risk to the environment.

A heat pipe is a sealed metallic tube **3**. Its inner surfaces are lined with a capillary material. The tube contains a liquid under its own pressure, which enters the pores of the capillary material, thus wetting all internal surfaces. The application of heat at any point along the surface of the heat pipe causes the liquid at this point to boil and enter a vapour state. When this happens, the liquid picks up the latent heat released by evaporation. The gas, which then has a higher pressure, shifts inside the tube to a colder location, where it condenses. In so doing, the gas transfers the latent heat from the input (evaporator section) to the output (condenser section) end of the tube. Heat pipes have an effective thermal conductivity several hundred times that of copper and they can be built in almost any size and shape.

Thermal modelling

The decision to use heat pipes for the internal cooling necessitated carrying out a number of studies of heat pipe behaviour and materials in order to come up with an appropriate design. Modelling based on 3-D finite elements enabled the designers to predict the temperature distribution inside the transformer in static and dynamic modes **4**. The SIDT team was thus able to compare hot points measured during, eg, the cold load pick-up test with the thermal model values **5**. This modelling provides essential design support.

Modelling has also shown that, with a different coil and core arrangement, there is no need for a cooling heat-pipe system for units rated 100 kVA and under.

Heat pipe performance

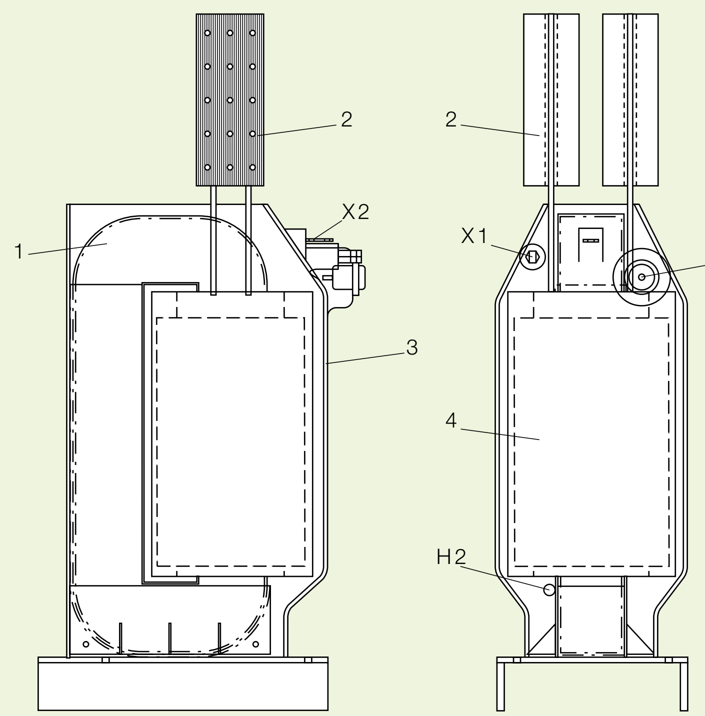
Heat pipes evacuate much of the internal heat generated by the transformer windings and magnetic core. In the case of the Hydro-Québec transformer, heat-extraction has been assessed at 42 % of total losses when the transformer is operating at full load, ie 167 kVA. The internal temperature is thus lowered at the hottest point, at the heart of the transformer. By comparison, an otherwise identical transformer without heat pipes would be limited to a capacity of about 100 kVA and would have a limited overload capacity. In addition, the tempera-

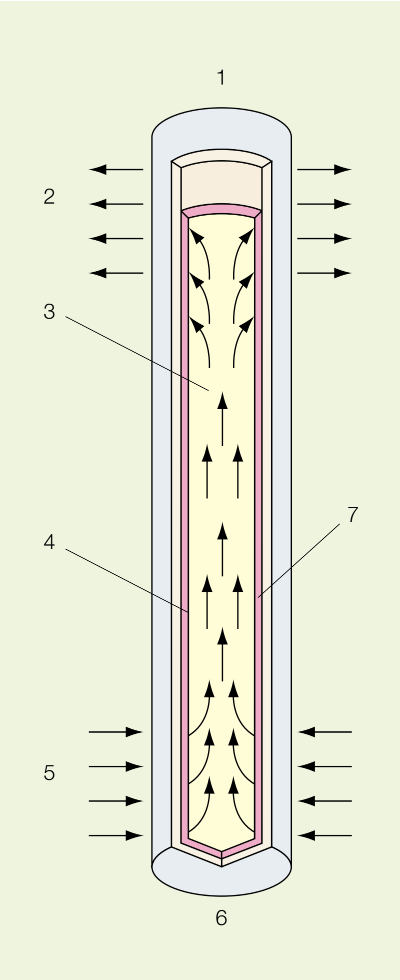
Table 1:
Technical data of the prototype SIDT transformers in service with Hydro-Québec

Type	Single phase
Power	167 kVA
Primary voltage	14.4 kV
Secondary voltage	347 V
Cooling	AN
Frequency	60 Hz
Max temperature	100 °C
Noise level	49 dBA
Impedance	4.00 %
No-load losses	420 W
Load losses	940 W
Width	512 mm
Height	1852 mm

Main components of the Solid Insulation Distribution Transformer (SIDT) **2**

1 *Core*
2 *Heat pipes*
3 *Outer shell*
4 *Windings*
H1, H2 *Primary terminals*
X1, X2 *Secondary terminals*





Working principle of the heat pipe **3**

1 *Condenser*
2 *Heat extraction*
3 *Vapour*
4 *Capillary material*
5 *Heat absorption*
6 *Evaporator*
7 *Liquid*

ture at the hottest internal point would reach about 140 °C. The use of heat pipes allows the SIDT to overcome these limits (ie, to increase power, lower temperature at hot points and increase overload capacity) **6**.

Test behaviour

The SIDT was put through a series of routine, type and special tests. The special tests were as follows:

- Short-circuit resistance
- Cold load pick-up tests (five cycles) **7**, **8**
- Low temperature
- Thermal shock
- Handling
- Electromagnetic field measurements
- Immersion tests in a saline solution (one month) **9**

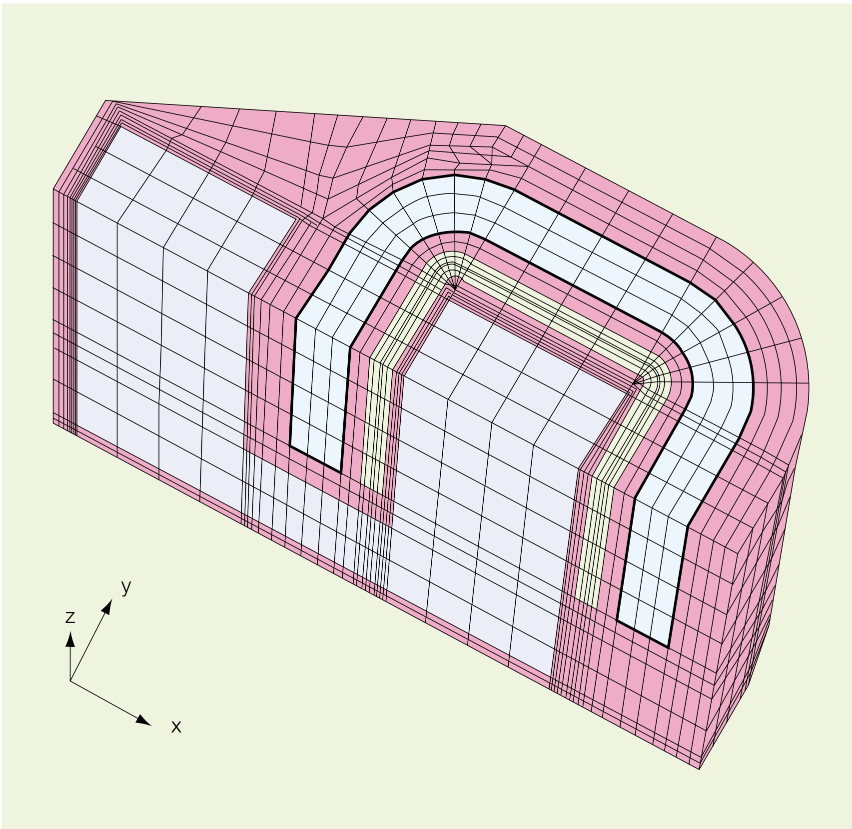
The cold load pick-up tests **7** demonstrated that the SIDT can operate normally for 20 days under severe loading conditions. Long-term durability of the heat pipes was demonstrated by exposing a set of pipes to 1,000 heating and cooling cycles. After the 1,000 cycles, the heat pipes were still operating normally. The final test focused on severe operating conditions. An energized unit was completely submerged for one month in a saline solution with a very high chloride content. The SIDT passed all of these tests with flying colours, and is thus expected to have a very long useful life.

Cold load pick-up test

The cold load pick-up test is a special test required by Hydro-Québec. During the test the transformers are subjected to five heat-run cycles corresponding to extreme service conditions. The transformer was energized during the test at its nominal voltage. Each cycle comprised the following steps:

- Heat-run at 100 % load until the temperatures reached equilibrium
- Overload at 140 % for one hour
- Simulation of loss of power for four hours
- Overload at 168 % for three hours

3-D model used to determine the temperature distribution inside the SIDT **4**



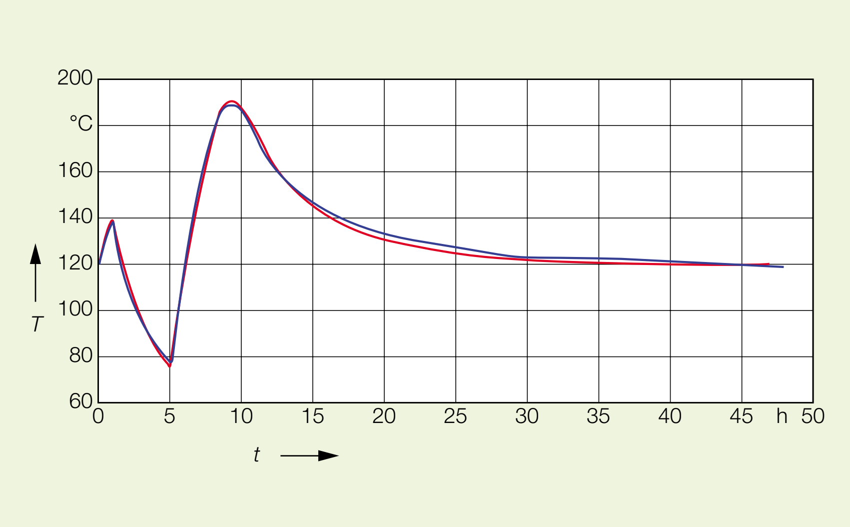
- Ramping-down for three hours to 100 % load
- Hold at 100% until equilibrium is reached

Monitoring under operation (demonstration phase)

On March 8, 1996, a demonstration phase was launched in collaboration with Hydro-Québec. Three 167-kVA units (designated A, B and C) forming a three-phase bank rated 500 kVA, were tested and monitored extensively in a Hydro-Québec underground vault. Monitoring included on-line measurement of:

- Individual unit loads **10**
- Ambient temperature inside the vault **11**
- Temperature of each heat pipe
- Surface temperature of each unit
- Level of water in the vault

The findings show that SIDT technology is very well adapted to the severe operating conditions typical of Hydro-Québec's underground networks.



Comparison of values measured during the cold load pick-up test and values calculated using 3-D modelling **5**

T *Temperature*
t *Time*

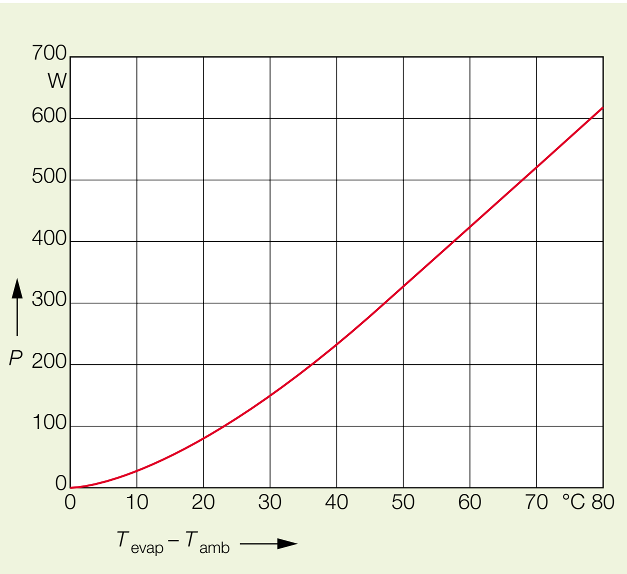
Red *Measured values*
Blue *Calculated values*

Patents and intellectual property

On August 12, 1997, CITEQ was granted a US patent covering three innovative features of the transformer design:

Heat extraction capacity of the heat pipes **6**

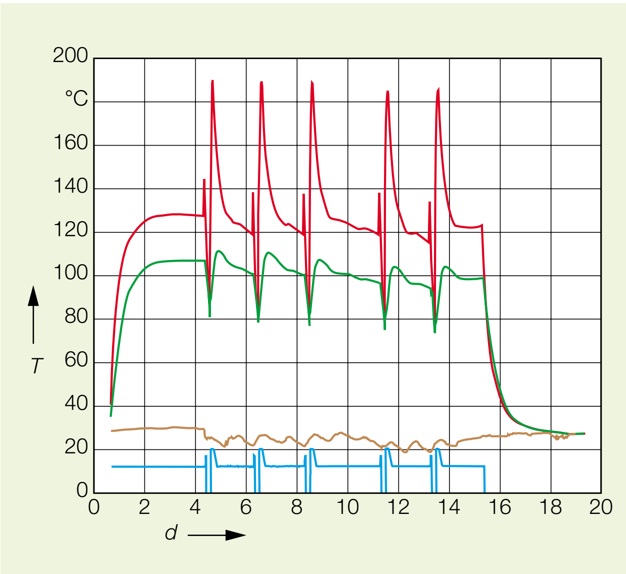
P *Power*
T_{evap} *Evaporator temperature*
T_{amb} *Ambient temperature*

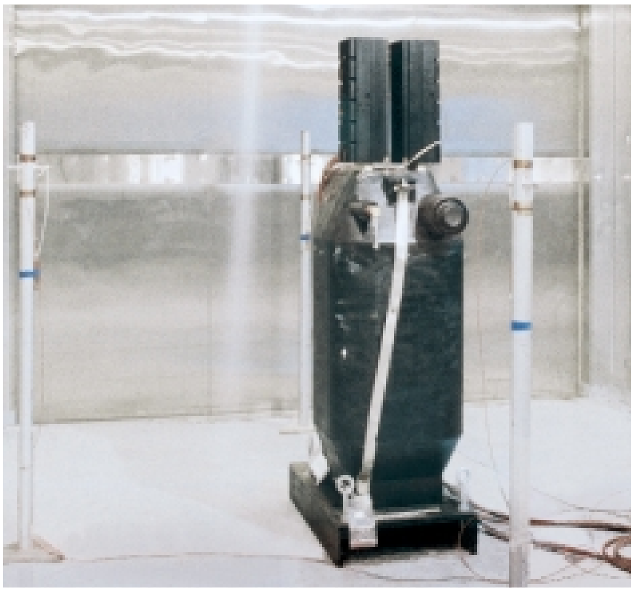


Results of coldload pick-up tests **7**

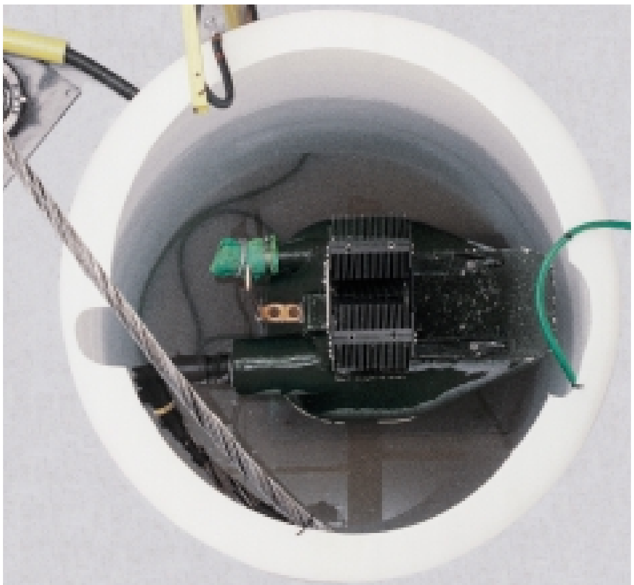
T *Temperature*
d *Days*

Red T_{18}
Green T_{37}
Brown T_{101}
Blue Primary current in pu





Coldload pick-up testing in a climatic chamber. Two transformers were placed in the chamber and left until thermal stabilization was reached at –10 °C. Afterwards, they were energized and loaded at 200 % for one hour. **8**



Immersion test: an SIDT was submerged in a saline solution for one month to confirm that it would operate safely and reliably under such severe conditions **9**

- Core cushioning
- Shielding method using a composite material (fiberglass and carbon fiber)
- Cooling method using heat pipes between the magnetic core and the LV winding

The patent covers various combinations of these three features for use in a transformer using a totally solid dielectric medium.

Cost-effective and environmentally friendly

The SIDT totally eliminates oil leaks, is corrosion-free and withstands severe weather and the test of time. It is a cost-effective system which can be safely installed underground at minimum cost.

The SIDT poses no risk of soil or groundwater contamination. As it can be safely located below ground, it eliminates the need for the noisy, unsightly substations required by above-ground systems. It is truly an environmentally friendly system.

Reliable and safe

The SIDT reduces the risk of distribution system failures even in the event of major weather disturbances such as ice storms, hurricanes, tornadoes and earthquakes. Thanks to its design, it can withstand the most severe weather, while its exclusive, corrosion-proof solid insulation gives it a longer useful life than any other type of distribution transformer. No preventive maintenance is required, and the SIDT can be buried directly in the ground for many problem-free years.

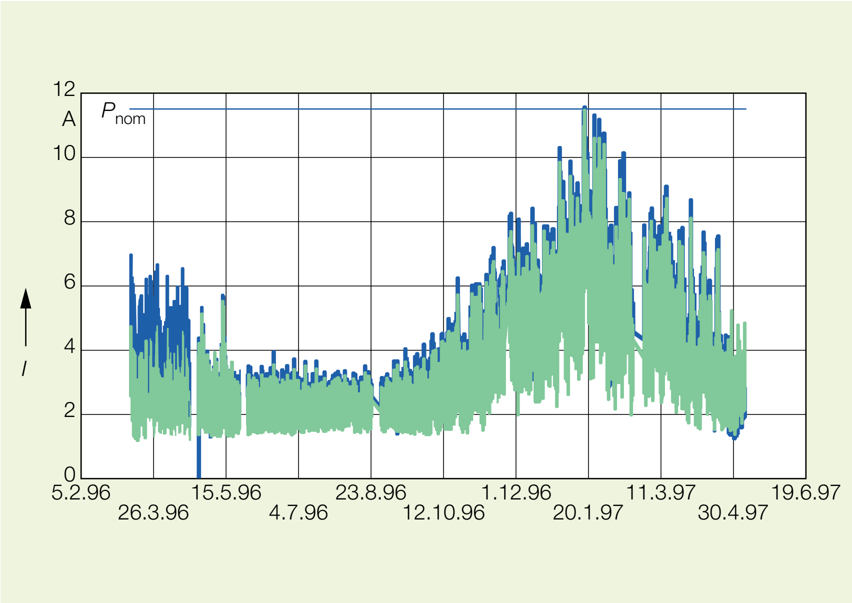
By opting for SIDT technology, utilities can reduce operating risks to virtually nil. The Solid Insulation Distribution Transformer contains no flammable or volatile liquids, thus eliminating fire hazards and the risk of explosions.

Features and advantages

- No flammable or volatile liquids present, thus eliminating fire hazards and limiting the risk of catastrophic explosions
- Eliminates underground contamination
- High resistance to short circuits
- Designed to work under water and in humid, dusty and dirty environments
- Silent operation
- Vertical or horizontal installation
- Environmentally friendly, generating no pollutants
- Eliminates incidental costs related to maintenance and monitoring
- Recyclable

Summary

The Solid Insulation Distribution Transformer enables utilities to operate their power distribution systems economi-



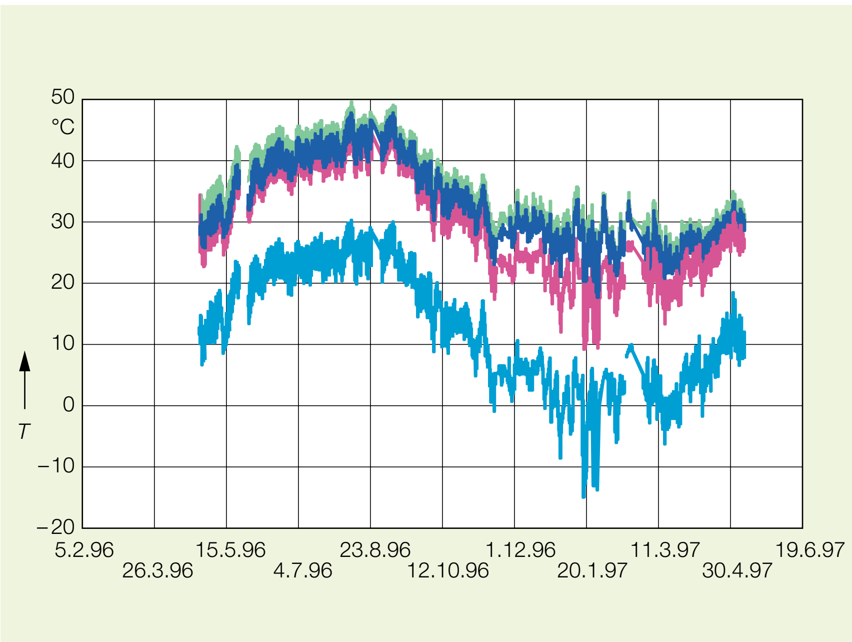
Results with the 167-kVA transformer units in service **10**

I	*Primary current*	Dark-blue	*Phase A*
P_{nom}	*Nominal load (1 pu)*	Green	*Phase B*

Results with the 167-kVA transformer units in service **11**

T *Temperature*

Dark-blue	*Mean heat-pipe temperature, phase A*
Green	*Mean heat-pipe temperature, phase B*
Pink	*Mean heat-pipe temperature, phase C*
Light-blue	*Air-vault temperature*



cally while meeting today's environmental standards. Designed for heavy duty and high reliability, it eliminates the high replacement costs associated with conventional transformers. Thanks to SIDT state-of-the-art technology, utilities can reduce outlays for maintenance, storage and disposal, while helping to ensure a brighter, greener future.

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