Mechanisms for Degradation of TR-XLPE Impulse Strength During Service Aging

Steven A. Boggs, *Fellow, IEEE*

***Abstract*—While the retained ac strength of TR-XLPE distribution cable appears to be quite good at about 80% of the ac strength of degassed, as-manufactured cable, the impulse strength appears to drop linearly over time and has been reported to drop by as much as 50% during the first two years of normal service aging before leveling off. In this paper, we discuss the mechanisms by which the impulse strength can degrade to a greater degree than the ac strength. Three frequency-dependent mechanisms, which include electrothermal, electromechanical, and electrical, have been identified.**

***Index Terms*—Distribution cable, EPR, service aging, TR-XLPE, XLPE.**

I. INTRODUCTION

DATA from field aging studies of TR-XLPE distribution cable indicate that while the ac breakdown voltage drops by about 20% relative to new, degassed cable and then remains relatively constant, the impulse strength drops substantially before leveling off. In one study, the impulse strength dropped by approximately 50% over two years of service aging, leveling off thereafter [1], [7]. Another study of field aged TR-XLPE cables has shown a similar but less dramatic approximately linear decrease in the impulse strength with time [2]. Clearly, the greater reduction in impulse breakdown strength relative to ac strength has to be a frequency effect. Three relevant mechanisms have been identified.

1) *Electro-thermal*: Heating and pressure of the water rise in the water tree channel as a result of the much greater current during an impulse relative to power frequency.
2) *Electro-thermal-mechanical*: The heating and pressure rise during the lightning impulse occur in 0.5 to about 2.5 μs, which results in generation of a shock wave in the dielectric which may promote impulse breakdown.
3) *Electrical*: At power frequency, the many small tree channels in the tip region of the water tree polarize appreciably which makes the water tree “look” like a relatively blunt defect. However, under lightning impulse conditions, these smaller diameter channels do not have time to polarize so that only the main root channel acts as a much more pointed defect.

Each of these mechanisms will be discussed after introducing a statistical model for water tree growth in TR-XLPE dielectric.

II. NATURE OF WATER TREES IN XLPE

Water trees consist of a dendritic pattern of electro-oxidized “channels” [3] in the range of 10 nm in diameter in the growth region which are self propagating because the electro-oxidation converts the polymer from highly hydrophobic to hydrophillic, so that water condenses into and travels preferably through the channels [4]. Over time, the channels lengthen through continued electro-oxidation at the channel tip region and expand in diameter through electro-oxidation of the channel wall. For distribution cable at normal operating voltage, the growth rate might be in the range of 5 mm in ten year or an average growth rate of about 16 pm/s (10^{-12} m/s) while the channel diameter grows to about 1 μm over the same time period (average growth rate of 3 fm/s [10^{-15} m/s]); however, we do not know whether the radial channel growth is relatively constant in time or if the channel grows in diameter more rapidly when it is small, for example, because the volumetric rate of electro-oxidation is constant.

III. MODEL FOR WATER TREE GROWTH IN TR-XLPE

As is well known, TR-XLPE insulation does not stop water tree growth, it impedes water tree growth, i.e., the number and size of water trees is reduced. As is also well known to those who have worked in the field, vented water trees grow primarily from ionic impurities at the dielectric-semicon interface [5] rather than from stress enhancements. The reduction in the number of water trees in TR-XLPE is probably as much the result of the greatly improved cleanliness of the semicon as the tree-retardant nature of the dielectric, which probably has more to do with the reduction in the size of the water trees. The use of “supersmooth” semicon probably has little effect on the number or size of water trees except insofar as the “supersmooth” semicon is also “superclean.”

TR-XLPE insulation consists of XLPE with a tree-retardant additive. At least some varieties of TR-XLPE dielectric contain a dispersion of hydrophillic molecules in the hydrophobic matrix. One logical assumption is that the hydrophillic molecules “stop” water tree channels, i.e., when a water tree channel “hits” a tree-retardant molecule, it stops propagating, probably because the hydrophillic molecule impedes condensation of water into any electro-oxidized region near it, so that the water tree cannot propagate beyond the hydrophillic molecule. However, this does not mean that water and ions cannot diffuse beyond the “tree-retardant” molecule.

Based on the hypothesis that a water tree channel grows until it encounters a water tree-retardant molecule, we can treat this as a mean free path problem. The tree-retardant molecules represent a randomly distributed set of points in the polymer ma-

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The author is with the Electrical Insulation Research Center, Institute of Materials Science, University of Connecticut, Storrs, CT 06269-3136 USA and also with the Department of Electrical Engineering, University of Toronto, Toronto, ON M55 1A1, Canada (e-mail: steven.boggs@ieee.org).

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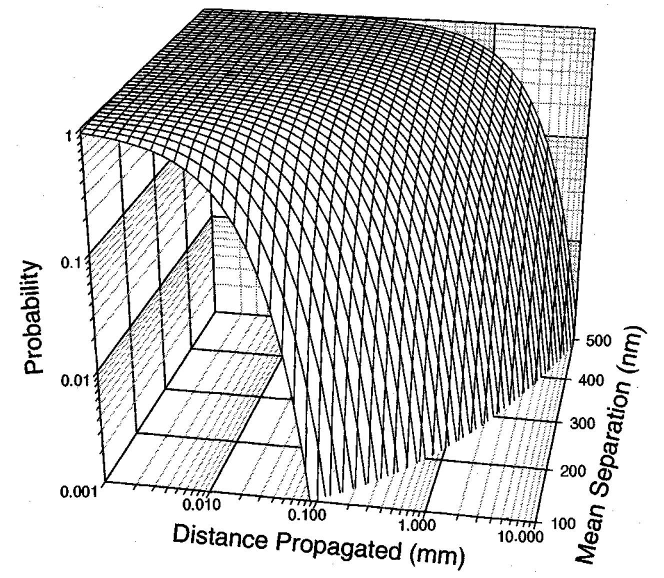

Fig. 1. Probability of a 10-nm diameter water tree channel propagating a given distance as a function of the mean separation between water tree-retardant molecules in the polymer matrix based on a mean free path computation.

trix which will stop a water tree channel, and the water tree (in the tip region) is a roughly 10 nm diameter channel propagating through the matrix. On this basis, we can compute the probability of a water tree channel propagating a distance x as a function of the mean distance between water tree-retardant molecules, as seen in Fig. 1.

The typical mean distance between water tree-retardant molecules in the polymer matrix is probably in the range of 200 to 300 nm, so that a typical water tree channel in TR-XLPE would grow to a length of about 0.3 to 1 mm (5% probability). Note that the predicted tree length is also a function of the diameter assumed for the water tree channel. If the channel diameter were set to 20 nm rather than 10 nm, the growth length would be somewhat less. In any case the above analysis provides a rational explanation and quantitative basis for water tree growth in TR-XLPE insulation which is in reasonable agreement with reality.

Vented water tree channels are known to branch, and often, numerous branches grow off a main branch which is rooted at the ionic contaminant at the dielectric-semicon interface. Thus, a limitation in the size of an individual branch would not necessarily stop extension of the water tree, as branches could form and extend until they hit a water tree-retardant molecule, branch again, etc. The limitation in water tree growth probably comes from diffuse electro-oxidation and the high water density around the water tree-retardant molecules after they stop a water tree channel. The water tree channel provides a supply of water, and the hydrophillic tree-retardant molecule probably provides a site for diffuse electro-oxidation by creating a high water region but suppressing water tree channel growth. Thus, the water tree grows to something like the 95 to 99% probability length (Fig. 1), at which point, sufficient water tree channels have "hit" water tree-retardant molecules to form a "surface" of diffuse water around the tree-retardant molecules at the outer reaches of the tree which impedes further growth.

Just because the water tree channel is "stopped" by the water tree-retardant molecules does not mean that the channels cease to evolve. As noted above, water tree channels grow in two directions, in length and in radius. Unfortunately, very few data on radial growth are available. The few available data (for example, from the Ph.D. dissertation of Ross) suggest that the water tree "trunk" channel in XLPE might be viewed as a cone with small, water filled cavities along its length. However, once the growth is stopped, the radial growth will probably continue so that the channel will probably evolve into a cylinder in the range of 1 μm in diameter, which appears to be the typical diameter of a mature water tree channel in its root region.

The conductivity of water in the water tree channel is another important issue. We know that substantial conductivity is required, as water trees will only grow from ionic impurities at the dielectric-semicon interface or if another substantial source of ions is provided. Water tree growth has been turned "on" and "off" by controlling the source of ions [5]. For relatively low concentrations of Nacl, the conductivity of water is about ten times the molarity. Thus a conductivity of 1 S/m is achieved with only 3 gm of Nacl per liter of water, and a conductivity of 0.1 S/m is achieved at a concentration of 0.3 gm/liter. Thus conductivities in the range of 0.1 to 1 S/m are entirely plausible, especially near the base of the water tree as an ion concentration gradient must exist down the water tree channel to transport ions to the growth region at the tip. Thus the water conductivity in the water tree growth region (where ions are "consumed") must be appreciably less than in the water tree base region near the source of ions.

IV. LIGHTNING IMPULSE-INDUCED ELECTRO-THERMAL/ MECHANICAL PHENOMENA

A semiconducting structure in a dielectric has a time constant to polarize, i.e., if a step field is applied across the dielectric, the overall field distribution has one or more time constants to go from an initial (capacitive) field distribution to a final (resistive) distribution, possibly with quasiequilibrium states between. In the case of a water-filled channel about 100 μm long and connected to the high voltage electrode in a typical cable geometry, the time constant for polarization of the channel is approximately

$$\tau = \frac{1 \times 10^{-19}}{r^2 \cdot \sigma}\ \mathrm{s} \qquad (1)$$

where r is the channel radius in meters, and σ is the water conductivity in Siemens per meter (Fig. 2). Thus, for a 0.5-μm diameter channel filled with 1 S/m water, the time constant for polarization is in the range of 0.4 μs. For a 0.25 μm channel with a conductivity of 0.1 S/m, the time constant is about 16 μs. These data were obtained through a transient solution of the electric field as a function of time after application of a step wave.

Since we are concerned with a lightning impulse waveform with a risetime of about 1.2 μs, we are interested primarily in time constants near this value. If the time constant is much longer than 1.2 μs, the channel does not have time to polarize appreciably during the waveform and any heat generated by current in the channel has time to diffuse away. In XLPE (thermal

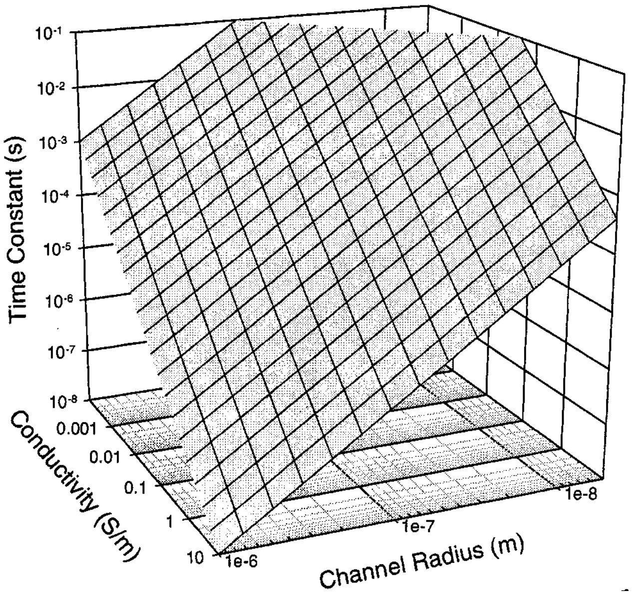

Fig. 2. Time constant for polarization as a function of tree channel radius and water conductivity based on (1).

diffusivitiy 1.7e-7 m^2/s), heat diffuses about 0.4 μm in 1 μs, and the diffusion distance goes as the square root of time. If the time constant is much shorter than the risetime, the cavity acts as a conductor and dissipates little heat from conduction. The worst case (greatest temperature rise) is when the impulse risetime is approximately equal to the dielectric time constant.

Computations were undertaken for a model water tree "trunk" structure shown in Fig. 3. The geometry involves plane electrodes separated by 6 mm with the water tree of Fig. 3 protruding from the high voltage electrode. The applied lightning impulse voltage is 350 kV across 6 mm, for an average field of about 58 kV/mm (2300 V/mil), which is on the low field side of where impulse breakdown occurs after field aging [1], [7]. Computations were undertaken for conductivities of 0.03, 0.1, 1, and 5 S/m (at 300 K). The computations include the temperature coefficient of conductivity for the water, which is typically 2.5%/K for an electrolyte, as well as high field conductivity in the XLPE, which is not a major effect. The maximum temperature rises and times at which they occur into the lightning impulse are shown in Table I. The temperature rise is appreciable over more than two orders of conductivity. Fig. 4 shows an example of the temperature on axis of the tree channel shown in Fig. 3. The temperature rise occurs in a very short time, which will lead to generation of a shock wave in the dielectric which could contribute to impulse breakdown. The change in energy from placing a long thin conducting element in a uniform field goes as the 2.8 power of the element length so that the energy available to heat the water should increase as roughly the cube of channel length while the water volume is proportional to length. Thus heating of the channel should increase rapidly with channel length.

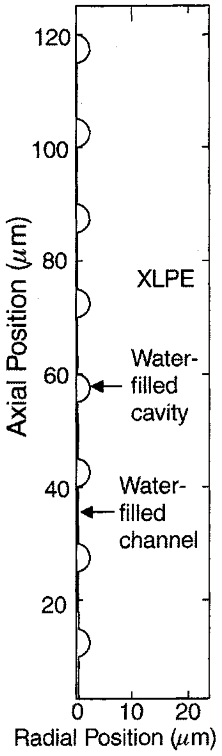

Fig. 3. Detail of water tree channel model. The channel is tapered with a radius of 0.5 μm at the bottom and about 0.2 μm at the top. An appreciably smaller radius than 0.2 μm is not practical as the ratio of largest to smallest feature in the problem is already 30 000 : 1 at 0.2 μm and requires about 25 000 triangles to mesh reasonably well for finite element analysis. Computation of the electric and thermal field distributions during a lightning impulse takes in the range of 24 h on a 700-MHz Pentium III PC.

TABLE I

EFFECT OF LIGHTNING IMPULSES ON A WATER TREE CHANNEL

Conductivity (S/m)	**Temperature Rise** (K)	**Time to Max Temp** (µs)
0.03	40	4
0.1	75	2.2
1	47	0.85
5	18	0.75

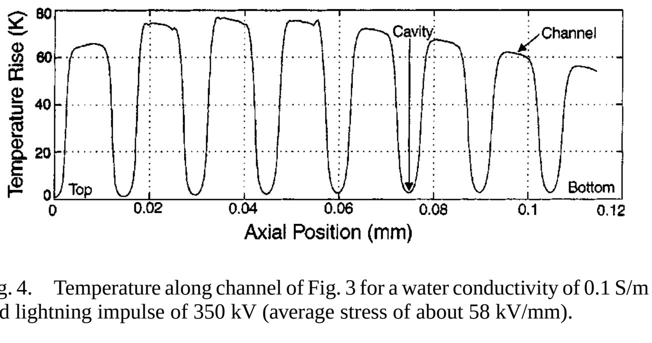

Fig. 4. Temperature along channel of Fig. 3 for a water conductivity of 0.1 S/m and lightning impulse of 350 kV (average stress of about 58 kV/mm).

The above computations can be compared with the energy available to raise the temperature of the water. We can imagine that just after a step voltage is applied, we disconnect the power supply. The system is now adiabatic, and energy must be conserved. We can compute the change in capacitance before and after the tree channel (Fig. 3) has relaxed (polarized) by computing the energy stored in the electric field and equating it to $(1/2)C \cdot U^2$, i.e.,

$$C = \frac{2 \cdot W}{U^2}, \qquad W = \frac{1}{2}\int^{V} \varepsilon \cdot E^2 \, dV \tag{2}$$

where W is the energy stored in the electric field, E, and U is the applied voltage and the integral is over the volume in which the electric field resides.

For the geometry under study when the channel goes from nonconducting to conducting, the capacitance of the channel changes by about 46e-20 F (0.46 aF). The change in energy of the system is then [6]

$$\Delta W = \frac{1}{2} C_i \cdot U_i^2 \left(1 - \frac{C_i}{C_f}\right) \tag{3}$$

or 28 nJ in the present case, where C_i and C_f are the initial and final capacitance (before and after polarization). The energy is dissipated primarily in the channels between the cavities, the total volume of which is about 3.3e-17 m^3. If all the energy were deposited in this water, the temperature rise would be about 200 C, not taking into account thermal diffusion into the XLPE, etc. The maximum temperature rise for 0.1 S/m is about 75 C and occurs at 2.2 μs. Fig. 5 shows a radial profile plot at 2.2 μs which indicates that the temperature is relative constant through the water but drops rapidly in the XLPE. Thus the effective temperature rise in the 0.4 μm beyond the water channel is about half the temperature rise in the water. On this basis, temperature rise in the channels would be about 110 C. In addition, some of the heat diffuses into the water cavities, as seen in Fig. 3. Thus the energy available from relaxation of the water tree channel is consistent with the computed temperature rise in the channel.

V. LIGHTNING IMPULSE INDUCED ELECTRICAL PHENOMENA

The time constant for relaxation of water tree channels has frequency-dependent implications for the electric field distribution in the water treed region. For example, power frequency corresponds to a time constant of $(2\pi f)^{-1}$ or 2.65 ms. according to (1), this corresponds to a channel of about 20 nm radius for a water conductivity of 0.1 S/m or about 7 nm in radius for a water conductivity of 1 S/m. Thus, even 5 nm radius would polarize appreciably, as is necessary for water tree growth at power frequency. Thus at 60 Hz, relatively small channels can polarize. However such channels would not polarize appreciably during a lightning impulse, which means that they would act as a dielectric rather than as a conductor. Only the largest cross section channel(s) near the root of the water tree would polarize appreciably during a lighting impulse, as shown by the computations in the previous section. Thus, during power frequency testing, the water tree would appear as a relatively large, diffuse object with a degree of RC grading caused by polarization and partial polarization of the larger number of small water tree channels in the water tree tip region. However, under lightning impulse conditions, the water tree would appear as a rather sharp protrusion on the conductor semicon, as only the main tree channel would be polarized appreciably and act as a conductor. This dielectric mechanism is active even for tree "trunk" channel conductances which are too large to result in substantial power dissipation. This mechanism explains why the small tree channels near the tip of the water tree do not shield the main channel and why the energy discussed in the previous section is not spread over a large volume of small tree channels, as such channels act as dielectrics during the relatively rapid lightning impulse, although they must be at least partially polarizable at power frequency to facilitate water tree growth.

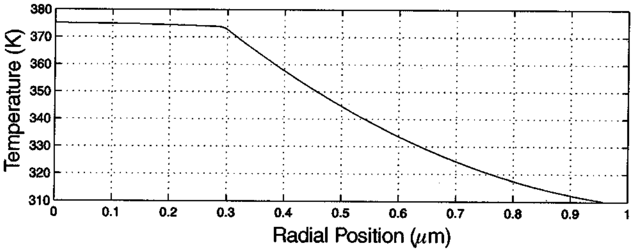

Fig. 5. Radial temperature profile at 2.2 μs for 0.1 S/m water conductivity near the middle of the water tree channel of Fig. 3. The temperature is relatively constant within the water and drops rapidly in the XLPE.

Unfortunately, finite element simulation of large numbers of very small water tree channels is impossible for a number of reasons. However a simulation was undertaken for a main channel with one "branch" at about 45° to the main channel. Because this branch was off axis, it acted as a cone in the 2-D axisymmetric simulation. This branch acted to feed current into the main channel and enhanced its temperature rise. Thus side branches, if polarizable, are likely to increase the current density in the lower region of the main channel and increase the temperature rise therein. This will increase the thermal expansion induce pressure rise in the main channel as well as the severity of the shock wave generated by the very rapid temperature rise.

VI. DISCUSSION

Three phenomena have been identified which can contribute to the reduction in impulse strength as a function of time during water tree evolution without having an "substantial" effect on the ac strength. However the suggestion often seen in the literature that the ac strength of TR-XLPE does not drop with time is misleading. The issue is the appropriate "initial" strength of TR-XLPE. As is well known, the ac strength as-manufactured of TR-XLPE cable is reduced as a result of volatile cross linking byproducts left in the dielectric. If such "virgin" TR-XLPE is tested to failure at power frequency, it normally fails as a result of thermal runaway. However if the cable is cooled (e.g., placed in water) during such a test or degassed prior to such a test, the ac strength increases substantially, by the range of 20%. Such degassing occurs fairly rapidly in service. Thus if we take the ac withstand in this degassed state as the initial ac breakdown strength, then the ac breakdown strength typically drops by the range of 20% during service aging, presumably as a result of water tree growth. Thus in considering the effect of water trees on the dielectric strength of TR-XLPE cable, a 20% reduction of ac strength and up to 50% reduction in impulse strength (over two years of service aging) appear to be the appropriate measures. The field data suggest that both the ac and impulse strength drop before leveling off, with the drop in impulse strength being much greater than the drop in ac strength [1], [2], [7]. The leveling off of the ac strength probably corresponds to the water tree reaching its final size. The RC grading at the outer reaches of the water tree make the effect on ac strength relatively independent of time thereafter.

We know that the water conductivity in the water tree tip region must be lower than that in the water tree main channel/root region, as i) an ion concentration gradient is necessary to carry ions to the tree growth region and ii) even if another mechanism were to effect transport, a constant supply of ions is clearly required for continued tree growth [5] as ions are "consumed" through attachment to the tree channel walls, which implies a concentration gradient. We also know that partial polarization at power frequency is required for water tree growth [4]. Very small diameter water tree channels which polarize appropriately for water tree growth at power frequency are unlikely to polarize appreciably at 300 kHz, the frequency which corresponds to the risetime of a standard lightning impulse. Thus the many small channels in the water tree trip region are likely to form a relatively large, diffuse system of RC grading at power frequency but are not efficient in providing such field grading under lighting impulse conditions. Without this shielding/grading, the larger diameter, more conductive (shorter polarization time) main tree channel is left "exposed" as a stress enhancement for the lightning impulse. However if the main water tree channel is so exposed and has sufficient conductivity to polarize, it is very likely to dissipate appreciable power during the lightning impulse, with a resulting sudden increase in temperature which generates a pressure pulse (shock wave) which could initiate mechanical fracture and promote impulse breakdown. The exception to this would be if the water conductivity in the main tree channel is so large ($>$10 S/m) that little power is dissipated in the water during the lightning impulse.

Given the above analysis, we are left to contemplate why the lightning impulse strength drops linearly over time. Given the relatively small size of water trees in TR-XLPE, they reach their maximum size within a year or two. Once they have reached their limiting size, most of the change should come through evolution of the channel diameter, with a slow increase in channel diameter over time. Increase of the channel diameter(s) increases the number of tree channels and the length of tree channels which have a time constant comparable to the lightning impulse risetime. This both increases the stress enhancement caused by those channels as greater lengths polarize and act like conductors during the lighting impulse and increases heating of the channels by the lighting impulse. Even at relatively early stages of water tree growth, these phenomena are active. For example, the computations related to Fig. 3 were carried out on a water tree channel, which was only 0.12 μm long, which is far less than the final size of the water tree. Thus, both growth of the water tree and evolution of the water tree channels once the tree has reached its final size will contribute to a drop in impulse strength but have little impact on the ac strength for the reasons discussed above.

Probably the best approach to experimental investigation of these phenomena would be to take service-aged cable, apply lighting impulses below breakdown and then apply an ac partial discharge test to determine if any electrical trees had been formed. Once PD can be detected, locating the PD to within a cm or so along the cable is not too difficult under laboratory conditions. This small section of cable can then be dissected to locate the defect which caused formation of the electrical tree. This is probably the most definitive way in which the analysis put forward in this paper can be tested and refined to determine with greater certainty what causes the drop in impulse strength of TR-XLPE cable during service aging.

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Steven A. Boggs (F'92) received the B.A. degree from Reed College, Portland, OR, in 1968 and the Ph.D. and MBA degrees from the University of Toronto, Toronto, ON, Canada, in 1972 and 1987, respectively.

He spent 12 years with the Research Division of Ontario Hydro, working in the areas of soil thermal properties, partial discharge, high field-induced degradation of solid dielectrics, and SF_6-insulated systems. From 1987 to 1993, he was Director of Research and Engineering at Underground Systems, Inc. He is presently Director of the Electrical Insulation Research Center and Research Professor of materials science, electrical engineering, and physics at the University of Connecticut, Storrs, as well as an Adjunct Professor of electrical engineering at the University of Toronto.