Fifty Years of Progress in Modelling the Accumulation of Atmospheric Ice on Power Network Equipment

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***Abstract*— The twentieth century witnessed two stages in the development of models to estimate the accumulation of ice on power network equipment. The first stage consisted of analytical models, expressed as simple equations, which could be readily solved by hand or with a calculator. In order to achieve simplicity, these models relied on strong assumptions or constraints about the nature of the icing process. Some of them also incorporated experimentally based empiricisms. For all of them, the goal was to predict bulk ice accretion properties such as ice load. They did not include details of the icing process. The second stage consisted of simple numerical models. It began around 1980 and was pioneered by the present authors. New models were developed which endeavoured to account for the physical details of the icing process. These models required personal computers for their implementation. Nevertheless, numerous assumptions and simplifications were still made in order to keep the computational problem tractable. With the advent of ever increasing computational power, the twenty-first century has seen the development of yet another generation of models which we may call "supercomputer models". Some of these numerical models are by far the most complete in terms of accounting for the physical processes of icing. Others adopt a radically different approach to icing simulation. However, these exciting developments present a serious problem. The quality controlled field and laboratory data that are needed to verify these third stage models are scarce or non-existent. In this paper, we document the progress of ice accretion modelling for power network equipment and reflect on the need for future model development and testing.**

I. Nomenclature

IWAIS = International Workshop on Atmospheric Icing of Structures
L = Lozowski, Stallabrass and Hearty [31]
LGH = Lattice Gas Hydrodynamics
M = Makkonen [5]
MVD = Median Volume Diameter
NRC = National Research Council Canada

II. Introduction

Modelling icing on power network equipment, especially on cables, is a subject that has been reviewed and summarized extensively over the past several years [1]-[3]. So much so, in fact, that one wonders whether a new review is really warranted. Nevertheless, in response to the kind invitation of the IWAIS XI organizers, the current authors have endeavored to synthesize a brief history of icing modelling, with a view to pointing out the progress that has already been made over the past fifty years, and perhaps pointing towards the progress that is yet to be made. Unlike numerical modelling in some other fields, where there are teams of software developers, icing modelling for power network equipment has tended to be a rather solitary occupation. Consequently, significant progress has tended to be somewhat sporadic, arising whenever a bright new graduate student or post-doctoral fellow happens to come along. In recent years, there have been several of them. We can only hope that there will be more of them in the future.

To the IWAIS audience, we scarcely need to offer justification or motivation for considering icing modelling. Suffice it to say that, responding to the Great Ice Storm of 1998 [4], considered by some to be a one in many centuries event, will offer ample justification, for years to come, to those whose inquiring minds seek, through numerical simulation, to improve our understanding of ice storms, for the ultimate benefit of the citizens of all northern countries.

III. Analytical Models

Due to the complexity of the icing process (see Section IV), there is little hope of making accurate predictions of its rate by simple methods. Nevertheless, a number of attempts to do this have been made, most of which look downright primitive to a present day modeller. However, one must acknowledge that a need for design ice loads existed long before supercomputers, our modern understanding of icing physics and IWAIS Workshops. Besides, due to a lack of data on some of the relevant input parameters, simplifications and empirical equations are still included in current models, as will become evident in this review.

A. *Rime*

The classical empirical approach to estimating the rate of rime icing R (kgs^{-1}) is to apply the equation R = cV, where V is wind speed (ms^{-1}). In this scheme the icing rate depends on the wind speed only. The constant c incorporates the aerosol collision efficiency and the liquid water content, both of which are typically unknown. It also depends on the substrate. The constant c for this equation has been determined empirically for cables by Makkonen [5], based on data by Rink [6], Waibel [7], Baranowski & Liebensbach [8] and Ahti & Makkonen [9]. As one might expect, c varies with type of rime ice (particularly its density) and geographical location, with the result that this equation provides a poor correlation coefficient between measured and calculated R. Simple nonlinear equations have been proposed by Diem [10], but these too have little predictive value in individual cases. Nevertheless, since errors in the icing rate tend to average out over long-term events, an empirical approach of this kind has some validity in predicting cumulative ice loads, as shown by Zavarina et al. [11] and Sundin & Makkonen [12]. In fact this method has been widely used in practical engineering, such as estimating design ice loads for transmission lines, transmission towers and suspension bridges.

B. Glaze

In many regions, freezing precipitation is the basis for the design ice load of power lines, as the people of Quebec and Eastern Ontario well know after the 1998 Ice Storm. The first attempt to empirically estimate glaze icing due to freezing rain was made using precipitation amount as the sole predictor [13]. However, it was discovered subsequently that the correlation between precipitation amount and ice load is very low [14]-[15], suggesting that modelling based on more detailed physics is required. To that end, analytical methods were devised and have been used for over 50 years. Some examples are [16]-[18]. Still others, including the widely used MRI model (never published in the refereed literature) are mentioned in [20] and [25]. Attempts have been made to systematically compare these models, viewed as 'black boxes', against specially collected data sets for individual icing events [19]-[23]. However, the models require different and sometimes missing input, which makes objective comparison by this method difficult. Furthermore, models that behave well in limited tests of this kind may not predict correctly in the rare extreme events that are of interest in structural design. Consequently, Makkonen [24]-[25] considered the expected applicability of various analytical glaze icing models from a theoretical point of view and concluded that the Goodwin model [18], with a small correction, is preferable. A similar conclusion was arrived at by Jones [26]. *Other analytical freezing precipitation models include errors that should render them obsolete*.

The Goodwin [18] model gives the same prediction for wet growth and dry growth, because it ignores water shedding. Most of the other models, on the other hand, assume that the water not frozen on the cable is completely lost by shedding. Makkonen [25] showed that neither of these assumptions is reasonable at high air temperatures and precipitation rates. The excess water from the cable tends to increase the total load rather than decreasing it, because of icicle growth. This effect is a consequence of the greatly increased surface capture area of the deposit with icicles, and it is very important when the wind speed is high. The effect of icicles on the growth of ice loads can be properly taken into account only by numerical modelling that includes all the relevant physical processes and their interactions (see Sections IV and V).

C. Wet Snow

As for wet snow, the empirical methods are still up to date and form the basis for current modelling. Snow particles bounce very effectively [27]. For dry snow, the sticking efficiency is essentially zero, although some dry snow accumulations have been observed under generally light wind conditions [72]-[73]. When there is a liquid layer on the surface of the snow particles, they tend to stick, so that with small impact speeds and favorable temperature and humidity conditions, the sticking efficiency is close to unity for very wet snow. However, because there is no detailed theory for the sticking efficiency of wet snow, the estimation methods are empirical equations based on laboratory simulations and some field observations [1], [28]. The best first approximation for the sticking efficiency on cylindrical objects [29] is that it is inversely proportional to wind speed V, becoming unity when $V< 1\ ms^{-1}$. Air temperature and humidity also affect the sticking efficiency, but there are presently not enough consistent data to take them into account, despite several experimental studies of this problem ([1] pp. 70-72). However, as pointed out above, snow does not accrete effectively when it is dry, i.e. when the wet-bulb temperature is below 0°C [30]. This criterion is very important because it allows determining the duration of wet snow events using climate data.

The snow content in air must, of course, be estimated for snow accretion modelling. It depends on the fall speed of snowflakes, for a given (measured) precipitation rate. This dependence produces an additional complexity to the modelling, because the fall speed depends on the shape, size and wetness of the snow particles. One way to circumvent this problem is to try to correlate the snow content with visibility and use the latter as the predictor for wet snow accretion. Based on this idea, Makkonen [30] proposed a simple equation for the wet snow accretion rate R_w ($kg\ m^{-2}s^{-1}$), viz. $R_w = 2.1\ \lambda^{-1.29}$, where λ is the visibility in metres.

There is a need for more research on snow accretion on cables, to fill the present gaps in our understanding of the physics of snow accretion and the extent of its occurrence and damage.

IV. Physical Models

Analytical models, that reduce the complexity of the icing process into a single formula for ice load, were appropriate to the time of slide rules and hand calculation. They are still valuable for making quick estimates. In some instances such as wet snow, they remain the “state-of-the-art”. However, the advent of personal computers in the 1970's led to the development of more complex icing models, in situations where our understanding of the physics of icing was sufficiently profound.

The six principal physical components of the icing process are: 1. the fluid dynamics of the airflow around the icing object; 2. impingement of supercooled drops, which constrains the maximum possible ice load (since the ice load cannot exceed the total mass of supercooled liquid that impinges); 3. internal and external heat transfer, which controls what fraction of the impinging liquid is actually retained as the accreted load; 4. surface flow and shedding of unfrozen liquid, which can behave as an electrically conductive, thermal insulator on the surface; 5. ice growth behaviour, including growth direction and properties such as density, roughness and icicle formation; and 6. the response of the loaded cable, including growth, twisting and galloping, along with their feedbacks on the other components of the icing process. It is this latter factor which makes the problem inherently time dependent even under constant environmental conditions. Of course, the secular variation of environmental conditions can impose additional fast time scales (due to turbulent fluctuations) and slow time scales (due to storm development and motion).

Rather than attempting to review all such physical models from the 1980's and 1990's, we will focus on two models that were developed by the current authors, and point out how they addressed the physical components of the problem, thereby advancing the state of the art. We will also point out their deficiencies, with a view to indicating where improvements need to be made (and sometimes have already been made by more recent modellers).

A. Lozowski Model

One of the earliest of the physical models is that of Lozowski, Stallabrass and Hearty [31], first published as [32], and referred to here as L. Although this model was originally developed for application to helicopter icing, it could be used for in-cloud icing of fixed cables. This model considers the impingement of both supercooled cloud droplets and ice crystals, but comparison with experiments has shown that its treatment of ice crystal accretion is wrong. In the model, airflow is ignored and droplet impingement is taken into account by adopting the parameterization scheme of Langmuir and Blodgett [33], who used an analogue computer to determine the trajectories of cloud droplets impinging on a cylinder in potential flow. This scheme gives the distribution of collision efficiency over the upwind surface of the cylinder. Consequently, no actual droplet trajectories are computed by the model. Since airflow and droplet trajectory calculation are typically the most time consuming part of a numerical icing model (particularly the latter), circumventing them makes a model more efficient, but, in this case, it limits the model to describing small ice accretions that do not significantly alter the cylindrical geometry.

Because L is fundamentally an aircraft icing model, there is no Joule heating, and the external convective heat transfer is parameterized using the experimental data of Achenbach [34] for smooth and rough cylinders. This scheme ignores the feedback of the growing ice accretion on the airflow and heat transfer. A significant, innovative feature of L is its accounting for the surface flow of unfrozen liquid, also known as *runback*. A control volume, mass balance approach is used to handle this aspect of the model, rather than attempting to account for the detailed fluid dynamics of the surface liquid film. Essentially, this is a one step model, in which the computed initial ice growth rate is extrapolated over a finite time interval to predict local ice thickness over the upwind surface of the cylinder. Experiments conducted in the Altitude Icing Wind Tunnel at NRC show that the model performs well in predicting small rime accretions, but its performance degrades when attempting to predict larger, glaze accretions. Interestingly, because of its simplicity, L continues in use as a tool in an aircraft icing forecasting scheme for the German Military [35].

B. Makkonen Model

The second model we will discuss here was designed with cable icing in mind. The Makkonen Model, referred to here as M, was developed as part of a doctoral dissertation, which was preceded by a preliminary stationary model that appeared in 1981 [36]. It has subsequently been extended via new parameterizations of the collision efficiency [37], ice density [38] and a boundary integral calculation of the heat transfer coefficient on a rough cylinder [39][1]. A separate icicle growth model [40] has also been added. Here, we will consider the original 1984 version [5], without these improvements. Unlike L, M *assumes* an ice accretion that is uniformly distributed around the cylinder. One may conceive of such an accretion as arising on a slowly rotating cylinder. This assumption is justified by the limited torsional stiffness of power line cables, as shown by wind tunnel experiments [38], and by data archives of real long-term icing events in [41].

Like L, M parameterizes collision efficiency using a scheme based on Langmuir and Blodgett [33]. Similarly, the convective heat transfer distribution was originally parameterized, based on experimental data, although more recent versions use the integral boundary layer method to compute it. Because of the assumed cylindrical symmetry (uniform radial ice thickness), there is no need to consider surface liquid runback; however, shedding of excess unfrozen liquid is allowed, and its contribution to the overall external heat transfer is accounted for. In more recent versions, its contribution to icicle formation is also accounted for. Unlike L, M includes longwave radiative heat transfer, but this is

[1] It is interesting to note that [39] is the very first use of integral boundary layer methods to compute heat transfer for cable icing. We discovered subsequently that McArthur [76] had already used the method in an aircraft icing model. However, because of the general lack of interaction of aircraft icing and power network icing researchers, the work in [39] proceeded independently. Curiously, this method for computing heat transfer seems to have been overlooked in subsequent cable icing models, until very recently [58].

generally a small term[2]. M has seen limited experimental verification in the field, in large part because the cloud liquid water content and droplet size distribution data that would be necessary to make a valid comparison, are simply not routinely or easily measured. Unfortunately, this situation has not changed over the past twenty years. M has, however, been successfully verified in the laboratory [38],[42]. M and its later versions have been used in operational power line design in the USA, Canada and Finland. The CRREL model [43] is broadly based on the M model, with several differences. These include differences in the heat transfer parameterization, the precipitation rate – LWC relation, inclusion of solar and Joule heating in the CRREL model, inclusion of aerodynamic heating and sponginess in the M model, and differences in the treatment of icicle growth.

C. Model Assessment

Before we move on to examine early twenty-first century models, it would be prudent to step back for a moment and consider the advances and limitations of the two physical models we have just described. As physicists, we have an intuition that, by improving the physics of a model and making it more faithfully follow the natural processes, we should improve its predictive ability. This is probably true over the long run, but it has its drawbacks. Perhaps chief among these is that the models become sensitive to parameters and variables that are not routinely measured, such as cloud liquid water content and drop size distribution. If a model is viewed as a mathematical transformation that converts a vector of inputs (environmental and geometrical variables) to a vector of outputs (primarily ice load), then a model is clearly constrained if some of the inputs are unknown, and have to be estimated indirectly via proxy variables, or based on "typical" or climatological values. In addition, some of the physical processes may interact in non-linear ways that can affect model stability.

Some of the shared limitations of L and M are the empiricisms used to estimate collision efficiency and convective heat transfer coefficient. Since both are based on the assumption of a cylindrical substrate, any deviations from cylindrical symmetry will begin to violate their applicability. Another limitation is the use of a single, "representative" drop size rather than the full droplet spectrum. Typically, this is the median volume diameter (MVD) of the droplet spectrum [44]-[45]. This constraint is imposed partly to limit the time required for the computations. Since, consistent with Moore's Law, computer chip speed has increased by a factor of between 10^3 and 10^4 since 1980, the computer time argument no longer holds water. However, the input limitation argument remains valid. There are few instruments that can measure cloud droplet, drizzle droplet and raindrop size distributions and there are no standards for their calibration. So the prospect of measuring droplet size distributions for input to models is unlikely in the near future. Even the MVD is difficult to measure The multi-rotating cylinder method seems to work well [46]-[47], but unfortunately this method is presently manual and, therefore, rarely used.

Before leaving the physico-mathematical models of the 1980's and 1990's, we would be remiss not to mention the significant contributions made by a number of other modellers, along with their students and colleagues. The modellers include, but are not limited to: Ackley [48], McComber [22],[49],[50],[51], Poots [1], Finstad [37] and Jones [26],[43], who has made some important contributions to parameterizing ice density and droplet collision efficiency.

There is insufficient space here to do justice to a detailed discussion of the work and innovations of these pioneers, and so we will not endeavour to do so. We apologize to them and to anyone inadvertently left off the list, including a host of modellers working in the field of aircraft icing, who face many similar challenges to those of us working on the icing of power network equipment. Recent progress in aircraft icing modelling has been recently reviewed by Gent et al. [52].

V. SUPERCOMPUTER MODELS

We refer here to two classes of power network icing models that have appeared in the new millennium. For want of a better term, we refer to them as "supercomputer models" because they are both very computationally demanding.

A. Enhanced Physical Models

The first class consists of *enhanced physical models*. Originally developed in the 1980's for the modelling of aircraft icing [53]-[54][3], it is only very recently that such models have been developed specifically, and independently, for modelling icing on cables. In fact, the only example we know if is the model of Fu [55],[56],[58]. We are unaware of any use of modern aircraft icing models to predict icing on cables, even though, in principle, it should not be difficult to adapt one of them for this purpose. Perhaps this has not happened, in part, because aircraft icing modellers and power network icing modellers do not tend to collaborate with each other. Perhaps it is because many current aircraft icing models are proprietary. Even LEWICE [57], possibly the most widely used aircraft icing code, is publicly available only in the United States. Since the details of Fu's model are well described in his thesis [58] and elsewhere [55]-[56], we will not take the time to enumerate them here. Instead, we will describe the generalities of enhanced physical models, using aircraft icing models as references, and pointing out some similarities and differences with Fu [58] along the way.

While all of these models are fundamentally similar to L and M, inasmuch as they endeavour to represent physical processes explicitly, their physical verisimilitude and computational procedures have generally been substantially

[2] We might mention here that we are unaware of any icing model that includes shortwave radiative heating of the ice accretion by solar radiation, except the CRREL model.

[3] Aircraft icing modellers have taken to inventing fanciful names for their models such as TRAJICE, LEWICE, CANICE, ICECREMO, THERMICE, TURBICE and FENSAP-ICE.

enhanced. A number of the models are three-dimensional and time-dependent, in the sense of accounting for the feedback between the growing ice accretion and the multi-phase flow around it. Fu [58] is time-dependent but two-dimensional[4]. Typically they use modern CFD methods to solve for the airflow, and either Lagrangian or (more efficiently) Eulerian[5] techniques to solve for the local collision efficiency. Fu [58] computes a potential airflow, with separation, using the boundary element method, and couples it with an integral boundary layer model to determine the heat transfer distribution over the ice accretion. Some models, however, solve the full Navier-Stokes equations for both the flow and the heat transfer. A few icing models also solve the thin film equations for unfrozen surface liquid, typically making various assumptions (e.g. lubrication theory [71]) in order to do so [56], [59]. Most models, however, treat runback using a control volume approach, which works satisfactorily in two dimensions but encounters difficulties in three dimensions. Without an explicit thin film, however, the model accretion surface temperature, under glaze icing conditions, can be in error by several degrees. One of the consequences of the surface film flow is a rough ice surface. Attempts to simulate roughness of ice have also been made in some recent models [60],[61].

Early physical models such as L and M consisted of only a few hundred lines of code, typically written in BASIC. Codes for the enhanced physical models are typically much lengthier and this leads to additional challenges, beyond those of representing the physics. Code validation, maintenance and modification, code interfacing and visualization of the results are among them. Fu [58] has addressed some of these issues by using object oriented programming in C++.

B. *Morphogenetic Models*

Morphogenetic models are a very different class of icing model, that adopt a unique approach to representing ice formation physics. They were originally conceived by Szilder [60] as a way to estimate ice properties, such as density, and to deal with complex, discrete ice accretion structures such as rime feathers and icicles. So far, at least, the explicit simulation of rime feathers and icicles has defied even the most advanced enhanced physical models. Yet they occur quite naturally in morphogenetic models.

The roots of morphogenetic modelling can be found in other fields of endeavour, including cellular automata and discrete particle methods in fluid dynamics (e.g. lattice gas hydrodynamics – LGH [67]). Analogous discrete particle models have been introduced into thin film nano-engineering [68], and there are some analogies with algorithmic botany [69]. Unlike LGH, however, morphogenetic modelling has not yet been shown to be fully equivalent to solving the classical physico-mathematical equations that govern icing, along with their appropriate initial and boundary conditions. As a result, morphogenetic modelers of icing prefer to use the term *emulation* rather than simulation, to describe the results of morphogenetic modelling. And the results can be quite impressive (see [61], [70] in this volume for example). Nevertheless, morphogenetic modelling is still in its infancy, and we expect that, in the future, rigorous theoretical underpinnings will need to be developed, to establish the physical and mathematical equivalence of morphogenetic emulations and natural icing. For now, however, we content ourselves with describing their similarities. Morphogenetic models have been produced in two and three-dimensional versions. We describe them below as if they were three dimensional.

The essence of morphogenetic modelling is that an ice accretion is built up using discrete particles, one at a time. Depending upon their size, these discrete particles can be thought of either as individual droplets or as ensembles of droplets that behave in unison. A model can be lattice free, but it is more typical to construct the model on a three-dimensional, rectangular lattice with cubic cells. The cells may be empty or occupied by substrate or liquid/solid particles (heneceforth simply particles). Each cell holds a single particle. Boundary conditions for the problem are established by first filling appropriate cells with substrate particles and then specifying an algorithm that prevents liquid/solid particles from moving away from the substrate or into it, unless specific requirements are fulfilled that allow them to *drip* or to seek an internal *cradle location*. Initial conditions are established by specifying the impact location of a particle. This is done, as in physical models, by solving the trajectory equation for the particle, or by using a parameterization or Eulerian shortcut to determine the local collision efficiency distribution.

Once a particle has impacted, it begins a solitary random walk. Instead of solving a Lagrangian equation for particle motion on the surface, a particle's behaviour is determined stochastically, under the influence of certain behavioral tendencies[6]. Since the acceleration of surface liquid flow is typically small, its fluid dynamics consists of quasi-equilibrium behaviour, involving a balance of gravitational, viscous, surface tension and wind stress forces. In addition, heat transfer can lead to freezing.

The combination of these processes is emulated in morphogenetic models by using a Monte Carlo approach which gives rise to a "random walk" for each particle. Controlling this random walk are probabilities of motion that are related to the force balance and a probability of freezing related to heat transfer. Very importantly, particles may leave the surface by dripping, provided that they satisfy conditions that emulate the pendant drop formation that gives rise to

[4] Farzaneh (personal communication) has indicated that a three-dimensional version is under development.

[5] FENSAP-ICE uses the CFD airflow solution, along with droplet trajectory and aerosol mass continuity equations in Eulerian form, to produce a 3D solution for the droplet velocity and concentration over a fine grid throughout the flow.

[6] One should be careful not to push the psychological analogy too far, but it is fair to say that, instead of obeying certain physical laws, such as Newton's Second Law, the particles in the model are given *habits*, which incline them to behave in certain ways.

icicles. This algorithm leads to the growth of icicles in morphogenetic models.

At present, some of the microscopic model parameters are estimated using theoretical considerations, while others are deduced empirically by comparing the model results with experiments. In addition to simulating the detailed morphology of complex ice accretions, morphogenetic models have an intrinsic stochastic variability that emulates natural variability. Having been developed for simulating power network equipment icing, morphogenetic models are now being adapted for simulating aircraft icing [62].

C. Model Deficiencies

Here we merely enumerate, without elaboration, features that are missing in many (though not all) existing icing models. We expect that future model development will take some of them into account. They appear in no particular order since their importance will depend on the use to which the model is put.

1. computation of surface liquid flow [74]-[75]
2. supercooling of the liquid film
3. surface roughness effects
4. complete droplet spectra rather than MVD
5. droplet splashing, deformation and break-up
6. 3D effects including icicles, differential cable rotation, cable sag and angle between wind vector and line orientation
7. electric field effects on droplet trajectories and ice growth behavior
8. accretion ablation and shedding
9. spongy ice formation [65]-[66]
10. cable dynamics including twisting and galloping
11. effects of anti-icing and de-icing systems
12. mixed precipitation icing
13. solar radiation
14. proper consideration of Joule heating

In the considerations above, we have all but ignored two types of power network equipment, namely wind turbines [60] and insulators [63]. They are sufficiently unique that each deserves a review of its own.

VI. Conclusions and Recommendations

Over the past fifty years, huge strides have been made in the modelling of icing, both on aircraft and on power network equipment. We expect the rate of model development to accelerate in the future, as ingenious programmers combine their wits with ever faster computers, to devise better ways to represent and simulate the physics of icing. Perhaps someone will even find a way to combine traditional continuous modelling techniques with the new morphogenetic modelling approach. The expected progress in model development will, however, present its own challenges.

While innovation is paramount in advancing science, the application of new icing models will benefit from serious attention given to issues of standardization, interoperability and dissemination. Urgently needed also are controlled laboratory and field experiments to provide a comprehensive data set for model verification. Further, it would make sense to intercompare not only models but also the facilities in which those models are tested, keeping in mind that both model and experimental results should have error bars. Finally, it would be unwise to overlook the progress made in allied fields, particularly aircraft icing. Steps need to be taken to encourage the interaction of icing modellers in both areas, and to extend the community to modellers of icing on wind turbines, towers and insulators. Perhaps this is an opportune time to set up an organization analogous to the Aircraft Icing Research Alliance (AIRA), which provides a framework for collaborative research into aircraft icing issues.

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