Open-Pit Glacier Ice Excavation: Brief Review

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Abstract: The authors have compiled information on the fundamentals of open-pit glacier ice excavation from a variety of sources. These sources primarily include U.S. Army technical and scientific studies and peer-reviewed research on glacier ice-excavation activities and the properties and mechanical behavior of ice, but also the relatively few publicly available feasibility studies and environmental impact assessments published by private mining companies. While ice is technically a non-Newtonian fluid over long timescales, the authors suggest that it may be regarded as a low-density and low-strength rock, analogous to coal, for the practical purpose of ice excavation over short timescales. Three distinct ice-excavation techniques are reviewed: blasting, melting, and mechanical excavation, providing a case study of each. The authors summarize the unique advantages and disadvantages of each technique and conclude that an optimal open-ice-pit mining operation would most likely rely primarily on mechanical excavation and secondarily on blasting. **DOI: 10.1061/(ASCE)CR.1943-5495.0000057.** *© 2013 American Society of Civil Engineers.*

CE Database subject headings: Excavation; Glacial till; Arctic regions; Ice; Mining; Temperature effects.

Author keywords: Excavation; Glacier; Greenland; Ice; Mining; Pit; Strength; Temperature.

Introduction

Large-scale open-pit glacier ice excavation is becoming an increasingly relevant consideration for mining operations in cold regions. Several factors, including increasing global demand in natural resources, warming air temperatures and

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Note. This manuscript was submitted on May 10, 2012; approved on January 2, 2013; published online on January 4, 2013. Discussion period open until May 1, 2014; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Cold Regions Engineering***, Vol. 27, No. 4, December 1, 2013. © ASCE, ISSN 0887-381X/2013/4-223-243/$25.00.

Journal of Cold Regions Engineering 2013.27:223-243.

retreating glaciers due to climate change, improved mining technology and prospecting techniques, and political shifts such as a new governance structure in Greenland, are making the development of cold regions mineral deposits economically feasible (Anderson 2009; Emmerson 2010). A variety of past, present, and proposed mining projects have confronted unique glacier management challenges (Table 1). Open-ice-pit mining, in order to recover a subglacial mineral deposit, is dependent on safe and predictable large-scale ice excavation. Open-ice-pit mining is successfully underway at the Kumtor Mine in Kyrgyzstan (Kumtor Operating Company 2010; Fig. 1). In 2010, 9.9 mega tons (MT) of ice was excavated to manage the flow of the Lysii and Davidov glaciers into the Kumtor open-pit mine. These glaciers flow into the open-pit mine at annually averaged rates of 1.4 and 5.4 cm/day, respectively. Recently, an acceleration in ice flow into the Kumtor pit led to major excavation challenges (Els 2012). This highlights the importance of understanding the unique challenges associated with glacier ice excavation. A larger open ice pit, with an estimated peak ice-excavation rate of 36 MT/year, has been proposed for the Isua project in Greenland (London Mining 2011a, b). Finally, at the Kerr-Sulphurets-Mitchell project in British Columbia, Canada, a proposed open-pit outline intersects the present terminus of Mitchell Glacier. As mining progresses over the coming decades, however, Mitchell Glacier is expected to retreat to expose the ultimate open-pit outline without any ice excavation (Seabridge Gold 2008).

This review article draws on a variety of sources, including government reports, peer-reviewed literature, and publicly available commercial studies, to provide as

Table 1. Selection of Mining Projects Confronting Glacier-Management Challenges

Mine/prospect	Country	Mineral	Apparent status	Glacier-management challenge
Malmbjerg	Greenland	Molybdenum	Under review	Potential glacier traverse[a]
Isua	Greenland	Iron	Under review	Potential subglacial deposit[b]
Black Angel/ Maarmorilik	Greenland	Lead/zinc	Under review	Potential subglacial deposit[c]
Kerr-Sulphurets-Mitchell	Canada	Gold/copper	Under review	Potential subglacial deposit[d]
Svea Nord	Norway	Coal	Active since 2001	Subglacial mining[e]
Kumtor	Kyrgyzstan	Gold	Active since 1997	Open ice pit[f]
Granduc	Canada	Copper	Active 1971 to 1984	Intentional thermokarst[g]
TUTO	Greenland	Ice	Active 1955 to 1959	Ice tunneling[h]

[a] Citterio et al. (2009).
[b] London Mining (2011a).
[c] Angus and Ross (2006).
[d] Seabridge Gold (2008).
[e] James et al. (2005).
[f] Centerra Gold (2011).
[g] Eyles and Rogerson (1977).
[h] Rausch (1959).

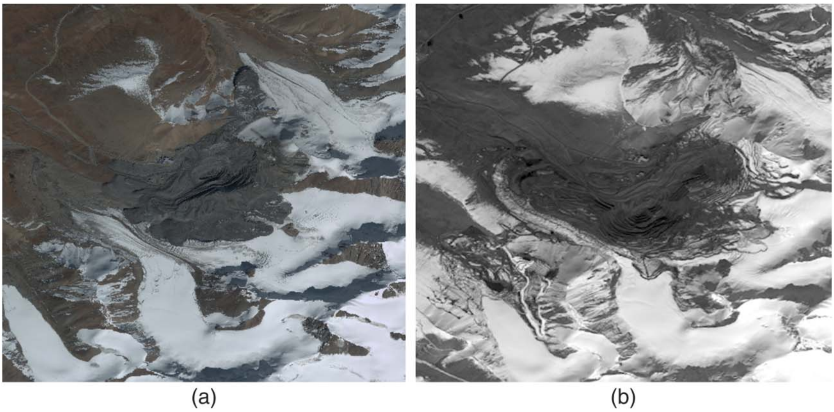

Fig. 1. The Kumtor Mine, Kyrgyzstan, features the intersection of an open ice pit with the Lysii and Davidov glaciers (frame width ≈ 7 km): (a) QuickBird-2 image acquired 10 April 2002 (with permission from DigitalGlobe); (b) WorldView-1 image acquired 26 September 2009 (with permission from DigitalGlobe)

comprehensive an overview as possible of the unique engineering and glaciological challenges of open-pit ice excavation. Due to significant differences in material properties and behavior ("Properties and Mechanical Behavior of Glacier Ice" section), ice excavation differs substantially from traditional rock excavation. As the majority of all publicly available ice-excavation research results from U.S. Army activities during the 1950s and 1960s, the authors briefly review the motivation and unparalleled scope of U.S. Army research in Greenland ("U.S. Army Activities in Greenland" section). Three distinct ice-excavation methods, with examples of each, are reviewed and compared: (1) blasting ("Blasting" section), (2) melting ("Melting" section), and (3) mechanical excavation ("Mechanical Excavation" section). Overarching ice mining challenges, issues unique to ice mining but independent of excavation method, are discussed separately in the "General Ice-Excavation Challenges" section.

Properties and Mechanical Behavior of Glacier Ice

In comparison to rock mining, ice mining presents several unique challenges. While ice is commonly referred to as the solid state of water, strictly speaking it behaves as a non-Newtonian viscous fluid; whereby shear strain rate is nonlinearly proportional to shear stress. By contrast, most rocks typically behave as elastic solids. As ice behaves like a viscous fluid, its relative strength is proportional to time. Over short timescales, ice is very strong; it can maintain a near-vertical ice cliff; while over long timescales, ice has virtually no strength; it flows like water. Acknowledging this behavior is important when designing open ice pits, as the geometry of a feasible short-term design (days to years) differs markedly from the geometry of a feasible long-term design (years to centuries).

The empirical relation between shear stress and shear strain rate describing ice rheology may be expressed as (Glen 1955):

$$\dot{\varepsilon}_{ij} = A\tau_{ij}^n \tag{1}$$

where $\dot{\varepsilon}$ = shear strain rate in per seconds, A = a temperature-dependent flow-law parameter in $/\mathrm{s}/\mathrm{Pa}^n$, τ = shear stress in Pa, n = a dimensionless constant, and the indices ij can take on values of x, y, and z in Cartesian coordinates. In a linear viscous fluid, n would equal 1, and $1/A$ would represent fluid viscosity. In ice, however, observed values of n range between 1.5 and 4.2 (with n typically taken as 3) (Paterson 1994). The flow-law parameter of ice (A), sometimes referred to as effective viscosity as its units differ from true viscosity (i.e., /s/Pa versus $/\mathrm{s}/\mathrm{Pa}^n$), is highly temperature-dependent. Typical values of A range from $5.1 \times 10^{-17}\ /\mathrm{s}/\mathrm{kPa}^3$ at an ice temperature of −30°C to $6.8 \times 10^{-15}\ /\mathrm{s}/\mathrm{kPa}^3$ at an ice temperature of 0°C. Thus, the shear strain rate, and consequent deformational ice velocity, resulting from a given shear stress varies by almost two orders of magnitude over a temperature difference of 30°C (Paterson 1994) (Fig. 2).

A variety of material properties of glacier ice, most notably density, uniaxial compressive strength, and fracture toughness, differ significantly from those of rock. While various rock types demonstrate a wide range of relatively high densities and compressive strengths [between 1,400 and 5,000 $\mathrm{kg/m^3}$ and 10 and 500 MPa, respectively (Lopez Jimeno et al. 1995)], the density and uniaxial compressive strength of glacier ice is significantly lower. Thus, ice may be considered a special-case end-member of the density-compressive strength curve for rock (Fig. 3). Fracture toughness is defined as the critical stress-intensity factor required to propagate a fracture. The fracture toughness (K_{Ic}) of glacier ice is typically between 0.08 and 0.15 $\mathrm{MPa \cdot m^{0.5}}$, independent of ice temperature (Schulson and Duval 2009). In comparison, the fracture toughness of rock is between 0.4 (limestone) and 3.2 (diorite) $\mathrm{MPa \cdot m^{0.5}}$ (Backers 2004). In addition to time, laboratory tests on a variety of prepared and natural ice samples, including glacier ice, indicate that the strength of ice is dependent on ice temperature and grain size and orientation (Butkovich 1954, 1959; Carter 1971; Hawkes and Mellor 1972; Haynes 1978; Michel 1978; Currier and Schulson 1982; Schulson et al. 1984;

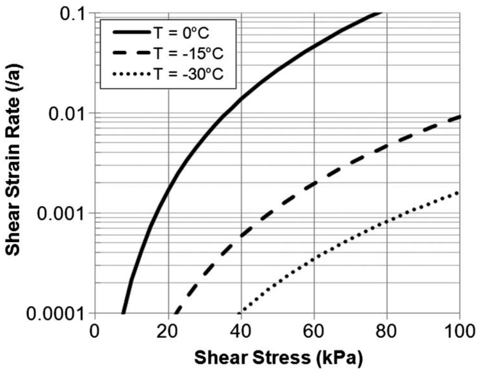

Fig. 2. Shear strain rate as a function of shear stress over a range of ice temperatures [Eq. (1)]

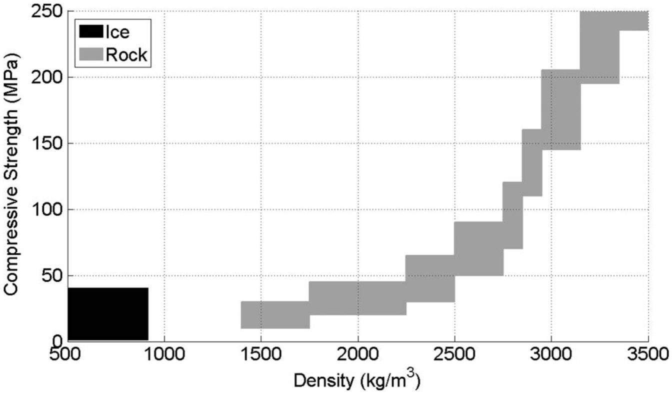

Fig. 3. Compressive strength and density of ice versus a variety of rock types [data from Butkovich (1959) and Lopez Jimeno et al. (1995)]

Lee and Schulson 1988). By comparison, rock strength is typically only dependent on grain size and orientation (Lopez Jimeno et al. 1995).

The uniaxial compressive strength of ice increases with decreasing ice temperature, from a minimum of ~3 MPa at 0°C to a practical maximum of ~40 MPa at −50°C (≈ -0.66 MPa/°C) (Fig. 4). Uniaxial tensile strength is generally an order of magnitude less than compressive strength and exhibits a negligible temperature dependence. Tensile strength ranges between ~1 and 3 MPa over the 0 to −50°C temperature range. Tensile strength, however, does significantly increase with decreasing grain size, from a minimum of ~0.5 MPa with a grain size of 10 mm to a maximum of ~1.5 MPa with a grain size of

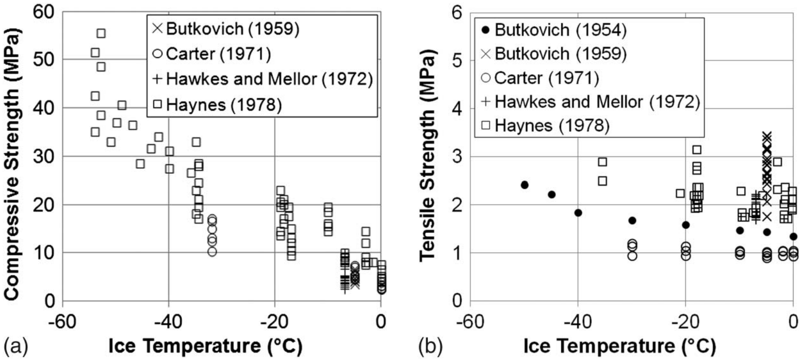

Fig. 4. (a) Compressive; (b) tensile strengths of ice versus ice temperature, for a variety of grain sizes and strain rates [data from Butkovich (1954, 1959), Carter (1971), Hawkes and Mellor (1972), and Haynes (1978)]; note the vertical scale of (a) is 10 times the vertical scale of (b)

1 mm (≈ -0.13 MPa/mm) (Fig. 5). Analogous grain-size-dependent variations in compressive strength are negligible in comparison to ice-temperature-dependent variations in compressive strength (Schulson and Duval 2009). Empirical evidence also suggests that the tensile strength of ice is dependent on the angle between grain c-axes and the tensile load (Carter 1971). As the crystal fabric of glacier ice can be heterogeneous over relatively short spatial scales, especially at a glacier margin, the cumulative effect of grain-load orientation is likely to be negligible in a large-scale ice excavation.

While the entire glacier thickness is comprised of ice in the ablation zone (where annual ablation or melt exceeds annual accumulation), significant depths of firn can exist in the accumulation zone (where annual accumulation exceeds annual ablation). Firn is an intermediate stage during the transition from snow to ice. Firn gradually achieves the density of ice through pressure sintering, whereby complex grain shapes gradually become rounded as water migrates from relatively high pressure tips to relatively low pressure centers (Paterson 1994). This process of densification is dependent on firn temperature as well as the presence of meltwater (Zwally and Jun 2002). Firn-to-ice transition depth (D in m), which is dependent on local climatology, can be estimated in the dry snow zone by an empirical relation based on data presented in Paterson (1994):

$$D = \alpha c + \beta T_{10} \tag{2}$$

where c = annual surface-snow accumulation rate in kg/m^2/year, T_{10} = the 10-m-depth firn temperature in °C [a proxy for mean annual temperature (Steffen and Box 2001)], and α and β = coefficients of 0.0611 years and -1.85 m/°C, respectively (Fig. 6). Ice excavation only occurs below the firn-to-ice transition depth within the accumulation zone. Firn excavation occurs above the firn-to-ice transition depth and is beyond the scope of this review (Walsh 1999, 2003).

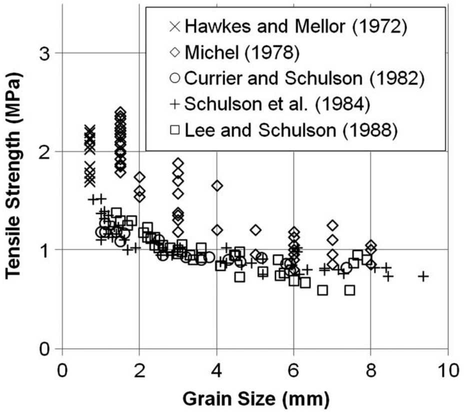

Fig. 5. Tensile strength of ice versus ice grain size, for a variety of ice temperatures and strain rates [data from Hawkes and Mellor (1972), Michel (1978), Currier and Schulson (1982), Schulson et al. (1984), and Lee and Schulson (1988)]

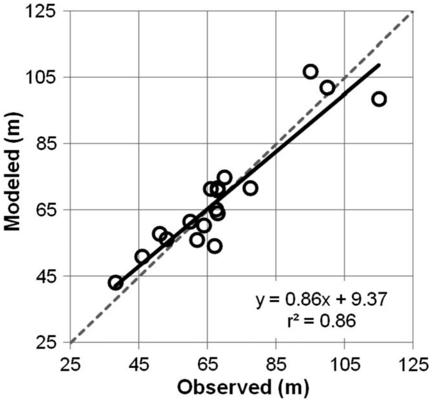

Fig. 6. Comparison between observed and multiple linear regression modeled [Eq. (2)] depth of firn-to-ice transition in the dry snow zone [data from Paterson (1994)]

U.S. Army Activities in Greenland

During the Cold War, the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) conducted ice-tunneling experiments at Thule Take Off (TUTO), in the ablation zone of the Greenland Ice Sheet (Fig. 7). The total ice volume excavated at TUTO over 5 years (30,470 m^3 between 1955 and 1959) is equivalent to <0.1% of the peak annual ice-excavation rate planned for the Isua project (Abel 1961; London Mining 2011b). U.S. Army research in northwest

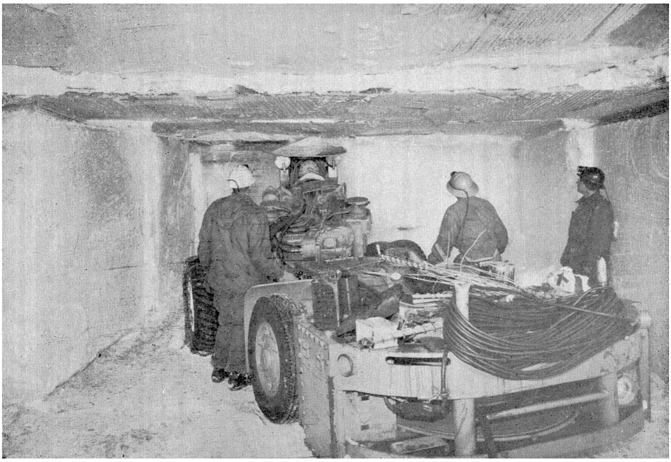

Fig. 7. Excavating ice in a TUTO ice tunnel, Northwest Greenland, using a 12-ton Joy 10 RU electric coal cutter in 1957 (Rausch 1959, with permission from the Colorado School of Mines)

Greenland, however, retains the title of the "most intensive... glaciological research program that ha[s] ever been envisaged," by the sheer volume of publicly available technical and scientific publications it produced (Martin-Nielsen 2012, p. 5). In comparison, privately operated projects have contributed very limited data on glacier ice mining to the technical and scientific communities through a small number of publicly available reports. Hence, understanding the motivation of, and resources committed to, the TUTO ice tunnels is valuable in order to appreciate why a similar glaciological campaign is unlikely to be repeated.

The TUTO ice tunnels were an initial phase of a 10-year feasibility study that examined deploying Intermediate Range Ballistic Missiles (IRBMs) within the Greenland Ice Sheet. Far from the U.S. population, and with ~80% of Soviet and East European targets within IRBM range, Thule, Greenland, was an appealing location to deploy IRBMs during the Cold War (Weiss 2001; Martin-Nielsen 2012). Additionally, subsurface ice tunnels provided numerous benefits, such as shelter from surface weather, concealment from aerial observation, and protection from aerial attack. With no previous experience excavating appreciable quantities of glacier ice and glaciology still a nascent discipline, the U.S. Army constructed a fully functioning 25-person subice camp within the TUTO ice tunnels between 1955 and 1959 (Russell 1961). Upon completion of the TUTO ice tunnels, the project leader recommended that "...with the exception of runways, an entire air base could be constructed under the ice" (Rausch 1959, p. 88). Camp Century was subsequently constructed at 10-m depth in the firn of the accumulation zone in 1959. Camp Century was a 225-person base, complete with ~3 km of firn-covered trenches, an operating subsurface railway, and portable nuclear generator (Weiss 2001; Petersen 2008; Martin-Nielsen 2012). The closure of Camp Century in 1965, primarily due to political considerations, marked the end of large U.S. military expenditure on fundamental ice and snow research. Between 1955 and 1965, however, the U.S. Army had gained unparalleled knowledge and experience in the technical aspects of large-scale snow and ice excavation.

Excavation Methods

This section reviews three distinct ice-excavation techniques: blasting, melting, and mechanical excavation. The authors draw upon experiences at the ice tunnels at TUTO, Greenland, the IceCube Project at South Pole, Antarctica, the Berendon Glacier, Canada, and the Kumtor Mine, Kyrgyzstan, as illustrative case studies of these techniques.

Blasting

As ice is a ductile material, its response to blasting is considerably different than that of comparatively brittle rock. Due to its ductile nature, explosions in ice result in deformation both with and without fracturing or a loss of cohesion (Livingston 1960). As a consequence of deformation without fracturing, peak shock-pressure values in ice are much lower than comparable values in an incompressible medium due to significant absorption of energy (Ingram 1960). A critical charge depth exists in ice blasting, below which deformation without fracturing dominates the response of surrounding ice to an explosion. Craters formed in glacier ice by explosions at near-critical depth have been observed to be domed, with fractures forming concentrically around the site of the explosive charge, rather than parallel to the surface of reflection as expected in more brittle substances such as hard rock (Livingston 1960). Optimum charge depth, where the maximum volume of ice is broken per mass of explosive (i.e., a trade-off between deformation with and without fracturing), is proportional to the cube root of the charge mass (Fig. 8). Optimum charge depth in glacier ice is between 0.64 and 0.74 of critical depth, depending on detonation velocity and mass (Livingston 1960; Barash 1966) (Fig. 9).

Powder factor, also known as specific charge (the mass of explosive necessary to fragment 1 m^3 of material in place), has been observed to reach a minimum of

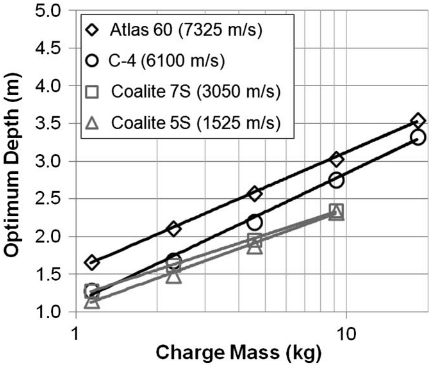

Fig. 8. Optimum charge depth versus charge mass for four types of explosives over a range of detonation velocities (given in parentheses) in pure glacier ice [data from Livingston (1960)]

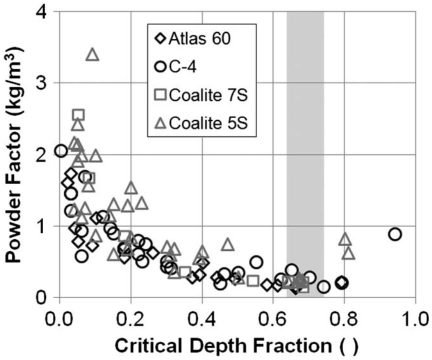

Fig. 9. Powder factor versus fraction of critical depth for four types of explosives in pure glacier ice [data from Livingston (1960)]; shading denotes the empirically derived fraction of critical depth equivalent to optimal depth (0.64 to 0.74 depending on explosive type and mass)

between 0.1 and 0.4 kg/m^3, depending on detonation velocity, for glacier ice charged at optimum depth (Livingston 1960) (Fig. 9). Limited empirical evidence indicates that shock velocity is ~3,500 m/s in glacier ice, regardless of explosive type and mass (Ingram 1960). While Russell (1961, p. 2) noted that even the lowest-velocity powders fractured glacier ice so that "... slabbing and ice falls persisted indefinitely," there appears to be a diminishing rate of return on increasing optimum depth or significantly decreasing powder factor by increasing detonation velocities above shock velocity (Fig. 8). In comparison to detonating explosives, deflagrating or low-brisance explosives such as black powder are characterized by subsonic explosion velocities with no shockwave and hence build up pressure considerably slower than detonating explosives (Lopez Jimeno et al. 1995). For the vast majority of the TUTO ice-tunneling effort, black powder was the explosive of choice, as it was found to produce a clean crater with large ice pieces that made for efficient loading and transport (Rausch 1959). Contemporary mining operations are more likely to use low-brisance explosives such as nitrocellulose or nitroglycerine rather than black powder due to their increased efficiency, reduced smoke development, easier handling, and environmental benefits (e.g., Akhavan 2011; Gokhale 2011). Higher-detonation-velocity explosives, such as C-3 or TNT, produce craters clogged with fine-shattered ice, so-called crushed muck, and plastically deform a much larger volume of adjacent ice (Livingston 1960).

Observations and numerical models of fracture propagation in rock indicate that crushing occurs when the dynamic elastic limit of a given rock is exceeded by the peak pressure or compressive strain of an explosive. Under these conditions, stress release by adjacent fractures interferes with the outward extension of fractures from the borehole. This results in shorter fracture-propagation lengths and intense crushing of rock near the borehole, with little or no fracturing away from the borehole (Hagan 1979; Cho and Kaneko 2004). The pressure of an explosive is proportional to detonation velocity squared, and accordingly, the transition from few long fractures to many short fractures appears to be a function of explosive P-wave velocity. Crushing wastes explosive energy and produces an overly fine muck. In hard-rock blasting, crushing can be remedied by increasing the diameter of the borehole relative to the diameter of the charge and inserting a fill material of desirable shock-wave propagation properties. Weak and/or highly porous materials, of which ice is both, are known to crush relatively easily with high explosives.

A significant portion of the TUTO ice tunnels were blasted using conventional burn cuts (several holes drilled in close proximity with one or more left unloaded), in which a main cut hole and eight perimeter trim holes were used to pull a 2.1 by 2.1-m tunnel forward ~4.6 m per blast sequence. A notable modification at TUTO was that the main hole was also charged, as it was found to clog with snow and ice. The charge holes were stemmed with either wet snow (Abel 1961) or sand (Livingston 1960) to prevent pressure release and direct the explosive charge into the glacier ice. Wet-snow stemming quickly freezes into a continuous solid, providing excellent explosive confinement. In the event of a misfire, however, it can be difficult to recover frozen-in-place loaded explosives (Rausch 1959). The TUTO engineers also discovered that the presence of liquid water could cripple blasting efforts. When drilling into cold ice (i.e., $< -5°\text{C}$) a drill can freeze into place, as water formed at the drill head migrates to, and refreezes on, colder regions of the drill (Livingston 1960; Bentley et al. 2009). Water-filled boreholes are capable of refreezing sufficiently fast to prevent the placement of an explosive sphere immediately after drilling. These problems are most severe when drilling at, or near, the glacier surface, where abundant liquid water is present during the melt season, and become negligible once drilling beneath a cold-based glacier, in the absence of liquid water (Rausch 1959).

Melting

One of the most significant differences between ice and rock mining is that ice offers the potential to be removed by changing its phase from solid to liquid. The scientific research community frequently uses hot water or steam drills to open boreholes through glaciers (Heucke 1999; Bentley et al. 2009). The basic principle behind hot water or steam drilling is relatively simple: (1) combust a fuel, typically diesel or jet, to heat either water or steam in a melter; (2) route the hot water or steam via hose from the melter to the desired ice face; and (3) apply the hot water or steam directly to the ice face. The sensible heat of the water or steam then heats the ice to the melting point and then changes its phase from solid to liquid. Given the relatively high specific-heat capacity of hot water in comparison to hot air [1.01 J/g/K for air at 100°C and 4.22 J/g/K for water at 100°C (Gieck and Gieck 2006)], hot-water drills have a better capacity to melt ice than steam drills. To produce either water or steam output, however, large quantities of input snow or ice must be melted, and high-flow drill systems can be overwhelmed by rapidly concentrating even trace sediment levels in the input snow or ice (Bentley et al. 2009).

Analogous to a powder factor in blasting, the authors may estimate a fuel factor for melting (F in $\mathrm{kg/m^3}$), defined as the mass of fuel required to change a unit volume of ice into water:

$$F = \frac{[c_p(T_0 - T) + H_f]}{E}\left(\frac{1}{N_1}\right)\left(\frac{1}{N_2}\right)\rho \tag{3}$$

where c_p = specific-heat capacity of ice [taken as 2,097 J/kg/K (Paterson 1994)], $T_0 = 0°\mathrm{C}$, T = the ice temperature in °C, H_f = the latent heat of fusion of ice [taken as 333,500 J/kg (Paterson 1994)], E = the energy density of diesel fuel [45.4 MJ/kg (Nektalova 2008)], N_1 = the dimensionless primary transfer efficiency (efficiency of fuel to water-energy transfer), N_2 = the dimensionless secondary transfer efficiency (efficiency of melter to ice-face transfer), and ρ = the density of ice (taken as 900 $\mathrm{kg/m^3}$). Off-the-shelf primary transfer efficiencies are ~80% with exhaust temperatures of 200°C, but refractory liners and additional transfer coils can yield primary transfer efficiencies of ~90% (Bentley et al. 2009). The authors therefore take N_1 as 0.8. Secondary transfer efficiency is influenced by energy loss through the hose, friction with the hose, energy lost to the atmosphere, and energy absorbed by debris/sediments within the glacier ice. Secondary transfer efficiency is thus highly dependent on numerous site-specific variables, especially hose length. The authors therefore take N_2 as ranging between 0.1 and 0.9, to encompass the entire range of plausible secondary transfer efficiencies. Using the aforementioned parameter values, Eq. (3) suggests that over the ice temperature range 0 to −20°C, fuel factor ranges between 10 and 85 kg of diesel fuel per $\mathrm{m^3}$ of ice (Fig. 10). These values do not include the energy requirements of ancillary

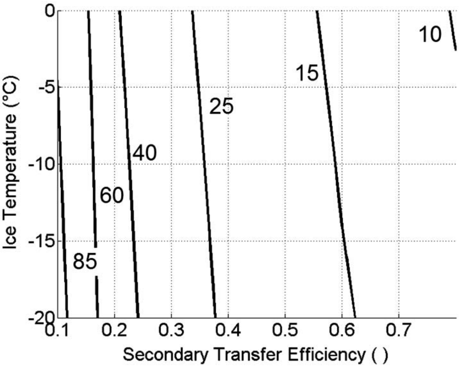

Fig. 10. Contour plot of fuel factor (F in kg/m^3; the mass of diesel fuel required to melt 1 m^3 of in situ ice) as a function of ice temperature (T) and secondary transfer efficiency [N_2; Eq. (3)]

units such as, for example, pumps, filters, and flow controllers (Bentley et al. 2009). Under the assumption that primary transfer efficiency is ~0.8, variability in fuel factor is much more dependent on secondary transfer efficiency than ice temperature. This highlights an inherent property of ice: the latent heat of fusion associated with phase change is orders of magnitude greater than the specific-heat capacity associated with temperature change (Paterson 1994).

The largest ongoing hot-water drilling project is Project IceCube at Amundsen-Scott South Pole Station, Antarctica (IceCube Collaboration 2001). Project IceCube aims to deploy a three-dimensional grid of neutrino sensors in the ice adjacent to South Pole Station, requiring 80 boreholes 60-cm wide and 2.5-km deep. The total efficiency of the Project IceCube hot-water drill (i.e., $N_1 \times N_2$), which pumps 88°C water at 760 L/min into the glacier ice, is estimated to be as low as 0.35. Given an optimized primary transfer efficiency of 0.9, this would imply a secondary transfer efficiency of ~0.4 (IceCube Collaboration 2001; Bentley et al. 2009). Similarly, at the TUTO ice tunnels, where waste-generator heat was reclaimed to melt glacier ice and provide the water supply for a 25-person subice camp, a total combustion to melt efficiency of 0.38 was realized (Russell 1961, 1965).

The Berendon Glacier in British Columbia, Canada, provides an interesting example of large-scale glacier ice removal by melting. Following a series of positive-surface mass balance years in the 1960s, it was hypothesized that the Berendon Glacier would sufficiently advance to bury the adjacent Granduc copper-concentrating terminal by the mid-1990s (Fisher and Jones 1971). The copper terminal was constructed only 20 m away from the glacier terminus, presumably during a time when glaciers were less widely recognized as dynamic features of the landscape (Eyles and Rogerson 1977). With the hope of counteracting an impending glacier advance, the Granduc Operating Company discharged 30°C wastewater directly onto the Berendon Glacier surface, at a rate of 13,500 L/min, year-round for 5 years (Eyles and Rogerson 1977). The wastewater stream quickly incised through the ice to the glacier bed, bisecting the terminal ~200 m of glacier tongue. By the end of the 5-year period the wastewater stream had become the effective terminus of the glacier, with 30-m-thick ice flowing at 28 m/year into the stream, where it was undercut by, and calved into, the stream. Although the anticipated glacier advance did not occur, the geometry of the Berendon Glacier was permanently modified by this intentional glacier thermokarst.

Mechanical Excavation

While significant differences in the properties and behaviors of ice and rock are especially apparent when employing the excavation techniques of blasting and melting, experience suggests that glacier ice may be regarded as a low-density, low-strength rock during mechanical excavation such as digging or grinding. The TUTO ice-tunneling project, which achieved 65% of the rated production of a rotating-chisel continuous coal miner, concluded that "modern [full-face] coal mining techniques [are] . . . adaptable to efficient and economical ice-mining" (Abel 1961; Russell 1961, p. 1). To date, no ice-excavation projects appear to have employed a rotating conical-grinding-action continuous miner. There are two main difficulties associated with using a continuous miner in glacier ice: the presence of debris bands and the presence of fine-ice particles. The TUTO ice tunnels project encountered a number of dipping debris bands, up to 275 m in-glacier from the margin and up to 10-m thick, ranging from silt bands with <2% solids by weight to cobble bands with >80% solids by weight (Rausch 1959; Swinzow 1962). While full-face mining machines are designed for coal seams [K_{Ic} of coal ≈ 0.1 to $0.2\ \mathrm{MPa} \cdot \mathrm{m}^{0.5}$ (Klepaczko et al. 1984)], which have approximately the same fracture toughness as ice [K_{Ic} of ice ≈ 0.08 to $0.15\ \mathrm{MPa} \cdot \mathrm{m}^{0.5}$ (Schulson and Duval 2009)], the debris bands in a glacier can contain much tougher rocks derived from the local geology [e.g., K_{Ic} of granite ≈ 0.7 to 2.5 (Backers 2004)]. Thus, when mechanically excavating the TUTO ice tunnels, despite using tungsten-carbide bits, the continuous miner had difficulty advancing in quartz silt and sand bands and encountered cobble bands through which it could not advance, and blasting had to be used (Fig. 7).

The presence of fine-ice particles or ice dust also contributes to accelerated abrasion of a continuous miner operating in glacier ice. This accelerated abrasion occurs when fine ice accumulates beneath the ripper chains, which normally ride in a tongue-and-groove arrangement on the cutting head, where it causes chain gibs to prematurely abrade away (Rausch 1959; Abel 1961). Additionally, the fine-ice particles are capable of freezing the cutting head in place during even brief pauses. The ice tunneling at TUTO overcame the difficulties associated with the presence of fine-ice particles through a combination of reducing the forward speed of the continuous miner, to give sufficient time for fine particles to leave the cutting head, and actively removing fine particles through a combination of heating and physical abrasion, by loosening the ripper chains to increase weight beneath the chains. Disposal of fine-ice particles during mechanical excavation has also been a major challenge in both historical firn tunneling at Camp Century, Greenland, and contemporary firn tunneling at South Pole, Antarctica. The Russell Miner, used by CRREL at Camp Century in the 1960s, disposed of fine-ice particles by both screw-auger mechanical displacement and vane-axial fan pneumatic conveyance systems. Both conveyance systems were prone to freeze-up, as the ice particles were inevitably heated during transport and refroze within the conveyance system. The next-generation CRREL South Pole Tunneling System, which uses a centrifugal fan pneumatic conveyance system, overcame freeze-up by improving the homogeneity of the ice-air mixture in the pneumatic conveyance system by introducing ice particles into an established air stream and increasing the distance between 90° joints in the conveyance system. Although challenging to design and implement, a pneumatic conveyance system has been found to be "vastly preferable" to any mechanical conveyance system (Walsh 1999, p. 10).

Acknowledging that caution must be exercised when comparing underice tunneling with open-ice-pit mining, the authors note that similar to the TUTO ice tunnels, the Kumtor Mine uses mechanical action such as the primary glacier ice-excavation technique (Kumtor Operating Company 2010). The Kumtor Mine, a traditional open-pit mine through the Lysii and Davidov glaciers (Fig. 1), was excavated with contemporary shovel-excavation techniques, using Liebherr 9350 hydraulic shovels and CAT 700 series haul trucks (Centerra Gold 2011). The resultant open ice pit has an ~30-m bench width to allow two-way CAT 700 traffic and an ~10-m bench height. In 2010, 9.9 MT of glacier ice was excavated from the Kumtor Mine using mechanical excavation (Kumtor Operating Company 2010). During this time, the challenges associated with glacier ice excavation were primarily associated with managing the flow of ice toward the open pit, rather than the actual excavation of ice (Centerra Gold 2011). The ice inflow, which reached a maximum of several decimeters per day during the summer, had been intensified by dumping waste rock directly onto Davidov Glacier in the past. Conventional hydraulic-shovel-and-haul-truck excavation has also been proposed to develop an open ice pit at the Isua project in west Greenland, with a projected peak ice-excavation rate of 36 MT/year (London Mining 2011a, b).

General Ice-Excavation Challenges

Once in-place ice has been loosened, either through blasting or mechanical removal, the resultant ice muck can be hauled in an analogous manner to rock muck. The swell factor of glacier ice is approximately 1.5, which means that excavating 1.0 m^3 of ice in place produces approximately 1.5 m^3 of broken ice muck. The swell factor of ice is slightly less than typical coal swell factors of 1.6 to 1.8. (Abel 1961; Lopez Jimeno et al. 1995) (Table 2). While the same haulage resources can transport equivalent volumes of ice and rock, the significantly lower

Table 2. Density and Swell Factor of Glacier Ice at the TUTO Ice Tunnels (Abel 1961) in Comparison to More Commonly Mined Resources (Lopez Jimeno et al. 1995)

Resource	Density (kg/m^3)	Swell factor
Coal	1,000–1,600	1.30–1.35
Copper ore	2,550–3,200	1.50–1.60
Ice	500–920	~1.50
Iron ore	2,650–4,750	1.40–1.60

density of ice means that between two and five times more haulage resources are required to haul the same mass of ice as rock. Most conventional waste-ice haulage systems, namely haul trucks or small-gauge rail car, are sufficiently effective in transporting ice muck that the rate-limiting step of ice mining is the removal of ice in place (Abel 1961; Centerra Gold 2011). While transporting large ice muck is almost completely analogous to transporting large rock muck, ice muck can potentially freeze to dump-box walls. Ice muck remaining in a dump box after dumping is a potential source of hauling inefficiency that is not encountered in traditional rock-muck transport. Innovative solutions, such as heated dump boxes or dump boxes lined with low-friction substances such as polytetrafluoroethylene (PTFE), may be needed to overcome this unique challenge. Proper treatment of fine-ice particles can also be challenging. Fine-ice particles can halt conveyor belt systems by causing slippage of drive and cleaning rollers. While this can be remedied by heating the conveyor belt, most contemporary operations use cold compressed air to keep moving surfaces free of fine-ice particles (Walsh 1999; Bentley et al. 2009). Once transported to the disposal area, freshly dumped ice muck has an angle of repose of 26°. The angle of repose increases to approximately 30° once the ice muck has been allowed to stand for longer than a day, which permits broken ice pieces to refreeze together (Abel 1961).

As may be expected, a serious challenge in ice excavation is the inherent slipperiness of ice. While the rubber-asphalt kinematic coefficient of friction is 0.67, the rubber-ice kinematic coefficient of friction is 0.15, which means that ice provides <25% of the traction as asphalt for wheeled vehicles [Office of Assessment Policy, Development and Administration (OAPDA) 2006]. With an ice-steel kinematic coefficient of friction of just 0.03, tracked vehicles provide only 20% of the traction of wheeled vehicles on glacier ice and are subject to lateral slide, especially when meltwater is present (Elert 2012). Loaded haul vehicles have difficulty negotiating ice road grades >3%, even when equipped with tire chains (Abel 1961). When describing the difficulties associated with working on ice, the TUTO ice tunnels project leader noted that "... personnel were constantly falling, and it was amazing that no serious accidents occurred" (Rausch 1959, p. 65). The TUTO ice tunnels project health records identify productivity losses of ~1.5 and 0.2% of potential worker hours due to sickness and accidents, respectively, with the accidents being "in no way related to the fact that the operation was working with ice" (Abel 1961, p. 33). These productivity losses were not significantly different from period non-ice mining operations. Similarly, high-altitude sickness, rather than ice-related accident, is the primary site-specific worker-safety concern reported at Kumtor Mine (Kumtor Operating Company 2010).

While spiked traction plates can be effective in facilitating vehicle movement, fine-ice particles tend to accumulate beneath the plate and separate spikes from the ice surface. Thus, traction plates are not a permanent solution to vehicle traction (Abel 1961). A thin gravel cover can be applied to ice roads to increase traction. The insulation effect of this gravel cover, however, can be problematic as it decreases the surface ablation of the gravel-covered road relative to the surface ablation of the surrounding ice. Due to this suppressed ablation, the relative elevations of supraglacial gravel-covered roads in Greenland (Davis 1971) and Spitsbergen (Humlum et al. 2003) have been observed to increase at >1 m/year above surrounding ice. Over a relatively short period of time, these gravel-covered roads become perched above the surrounding ice with steep side slopes and require substantial maintenance to mitigate hazards, such as toe failures, in order to maintain safe traffic flow. Due to the spatial heterogeneity and rapidity of perching, glacier-traverse roads with a theoretical design life of "at least 10 years" have been found to have a practical life of less than 5 years [Arctic Construction and Frost Effects Laboratory (ACFEL) 1963, p. 103; Davis 1971]. Ongoing ice-integrity monitoring, primarily using ice-penetrating radar, is essential for maintaining safe traffic flow over highly transient glacier-traverse roads. This monitoring ensures that ice strength is not compromised by crevasses or subglacial hydrological features before being accessed by heavy equipment.

During the summer melt season, surface ablation results in rapid changes to the glacier surface and meltwater generation. Mean annual surface ablation exceeds 3 m in some regions of the Greenland Ice Sheet. If distributed over approximately four melt season months, this is equivalent to ~5 cm per unit area surface ablation and runoff per diurnal cycle (Ettema et al. 2009). When equipment remains at the same location on ice, the equatorial side of the ice beneath the equipment preferentially melts and equipment migrates downslope over short timescales (Rausch 1959). Virtually every proglacial ice mining operation must contend with the inflow of surface meltwater by either diverting or pumping large volumes of water during the melt season. Despite optimizing meltwater diversion, the Kumtor Mine must pump as much as ~1,000 $\mathrm{L/s}$ of glacier meltwater from the pit mine during the melt season (Centerra Gold 2011). Developing ice berms, by preferentially suppressing ablation along a wide strip of glacier ice that intersects overland runoff upglacier from mining activities, appears to offer the best potential for permanent meltwater diversion. By comparison, ice trenches can be difficult to excavate and tend to fill with slush during the melt season (Rausch 1959). When on-ice access roads must cross a meltwater stream, employing the widest possible single-span bridge on crib-type abutments is preferable to attempting to route a meltwater stream through a culvert or narrow-span pile bridge. This approach minimizes the likelihood that highly erosive meltwater will come into contact with infrastructure. Prior to building a wide single-span bridge, an on-ice pile bridge that was sunk ~6 m into the glacier surface was completely eroded out by a modest meltwater stream over the course of 2 years near the entrance to the TUTO ice tunnels (Davis 1971).

When excavating an open ice pit, there is a high potential for large ice blocks to detach and fall from near-vertical faces, especially if the glacier is heavily crevassed or significant blasting has been employed (Rausch 1959). The presence of crevasses signifies locations where relatively high longitudinal normal stress gradients or longitudinal coupling stresses exist and the tensile stress of ice has been exceeded. Thus, the continuum mechanics normally used to describe ice flow as a function of shear stress break down in crevassed locations. Under the assumptions of the shallow-ice approximation to continuum mechanics (Paterson 1994), the shear stress driving glacier flow (τ) may be described by

$$\tau = \rho g H \frac{\partial z_s}{\partial x} \tag{4}$$

where ρ = glacier density in $\mathrm{kg/m^3}$, g = gravitation acceleration (9.81 $\mathrm{m/s^2}$), H = glacier thickness in m, and $\partial z_s/\partial x$ = dimensionless glacier-surface slope. While glacier-surface slope and thickness can be optimized over progressive excavation profiles in order to minimize the large-scale potential for crevasse propagation by minimizing glacier-driving stress, crevasse potential can never be truly eliminated at the small scale. For example, the large-scale 4 H:1 V ice pit profile of the Kumtor Mine is comprised of wide benches and near-vertical faces at the small scale (Centerra Gold 2011). Thus, similar to fractal theory, small-scale near-vertical ice faces prone to ice falls are an inherent feature of employing sequential benches in an open-ice-pit mine. Incorporating a minimum setback distance between the toe of a near-vertical ice face, and any downslope mining activity is likely the best strategy to minimize the negative consequences associated with ice falls. This minimum setback distance can be a function of local ice dynamics and the operator-accepted risk level. Thus, detailed monitoring of ice dynamics before and during excavation is a critical element for safe and economic ice excavation. Following the observational method to optimize safety and excavation (Peck 1969), useful ongoing monitoring data include glacier-surface deformation measurements as well as deformation measurements of the near-vertical free-ice face. Given the significant differences in properties and behavior of glacier ice in comparison to rock, these monitoring data should be collected at a much higher temporal frequency at ice-excavation sites, in comparison to traditional rock-excavation sites.

Summary Remarks

The authors have compiled information on the fundamentals of glacier ice mining from the numerous technical and scientific studies produced by the U.S. Army during the Cold War, peer-reviewed research on glacier-mining activities and the properties and mechanical behavior of ice, and the relatively few reports published by private mining companies that are publicly available. While ice strictly behaves as a non-Newtonian fluid over long timescales, it may practically be regarded as a low-density and low-strength rock for the short-term purpose of ice excavation. The strength of glacier ice is dependent first on ice temperature and second on grain size, with uniaxial compressive strength increasing with decreasing ice temperature and grain size. The fracture toughness of even the strongest ice is approximately the same as that of coal, which is less than the fracture toughness of even a weak rock such as limestone.

The authors have reviewed three distinct ice-excavation techniques: blasting, melting, and mechanical excavation (Table 3). Blasting is ideal for use in crevassed or sediment-rich ice, which may not be loosened by mechanical excavation, but requires the time-consuming drilling and stemming of blast holes. Melting avoids

Table 3. Primary Advantages and Disadvantages of the Three Ice-Excavation Methods Surveyed in This Review

Method	Advantages	Disadvantages
Blasting	Works in crevassed or sediment-rich ice	Tedious blast-hole drilling required
Melting	Relatively simple meltwater conveyance	Very energy intensive
Mechanical excavation	Uses conventional mining equipment	Difficult to maintain vehicle access

the difficulties associated with conveying ice muck and fine-ice particles, which are inherent to both mechanical excavation and blasting, but is extremely energy-intensive. Mechanical excavation can use conventional coal-mining equipment and was the preferred excavation technique at both the TUTO ice tunnels and the Kumtor open-ice-pit mine, but requires that vehicle access to the cutting face is maintained across highly transient glacier-traverse roads at all times. While each method has unique advantages and disadvantages, an optimal open-ice-pit mining operation would likely be primarily dependent on mechanical excavation and secondarily dependent on blasting. Ongoing monitoring of ice flow at relatively high temporal resolution is a critical element for safe and economic ice excavation, in order to develop and maintain the capacity to continually adapt to changing local ice dynamics.

For a variety of reasons, climate change and increased resource demand foremost among them, large-scale glacier ice excavation is becoming an increasingly relevant consideration for open-pit mining operations in cold regions. While ice excavation presents several engineering and glaciological challenges in addition to those associated with conventional nonice mining, the balance of evidence, embodied in innovative projects such as the TUTO ice tunnels and the Kumtor Mine, suggests these challenges can be feasibility-overcome. The authors speculate that the most difficult obstacle presently facing any industrial ice-excavation project is most likely the potential public perception of a mining company directly contributing to glacier loss (e.g., Urkidi 2010). While clearly not an engineering issue, this is another unique, but intangible, challenge that must be acknowledged as distinguishing ice mining from conventional rock mining.

Acknowledgments

BGC Engineering has provided consulting services to companies associated with projects discussed in this paper and appreciates their approval in writing about those projects. W.C. has provided geoscientist services to BGC Engineering. This paper is published with the permission of the Geological Survey of Denmark and Greenland. The authors thank Iain Bruce and Henrik Thomsen for reviewing an earlier draft of this manuscript. The authors also thank two anonymous reviewers for their insightful comments and constructive criticisms on this topic.

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