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WATERFALL MIST PLUMES: GENERATION, DYNAMICS, AND EXAMPLE FROM NIAGARA FALLS, CANADA/USA

M. Bursik and P. Case

Department of Geology, University at Buffalo, SUNY, Buffalo, NY 14260

ABSTRACT: Mist plumes are prominent features at waterfalls of sufficient discharge, and can occasionally be seen to be lofted to great height. Under the proper fluvial and atmospheric conditions, the Niagara Falls plume rises over 1 km. Here we show that waterfall mist plumes are driven upwards by buoyancy generated from the mechanism of mixing of aerosolized warm river water with cold air in a high-speed impact jet at the base of the falls. The plumes are generated with a periodicity that is a function of buoyancy or thermal flux.

INTRODUCTION

Those who have visited a large waterfall are familiar with a mist curtain (sometimes called a brume or veil) often hanging near the base. The curtain is comprised of water aerosol particles generated by break up at the base of the fall, and ejected into the atmosphere in a high-speed jet (Figure 1). The curtain occurs near the fall, or sometimes propagates slowly downstream. Occasionally, a plume generated from the curtain rises into the atmosphere. In the case of Niagara Falls, this rise can be over 1 km (Figure 2).

Waterfall curtains and plumes are in fact generated in a unique natural system. Once it plunges over the rocky crest, the Horseshoe Falls of Niagara descends 53 m to the Maid of the Mist Pool at its base (Gilbert, 1907). As the descending water strikes the pool, a high-speed jet of aerosolized water blasts from the impact site, rapidly mixing the water aerosol of the Niagara River with ambient air (Figure 1). From this air-water mixing region, the curtain ascends into the plume. Intuitively, two possible mechanisms for plume rise present themselves: 1) atmospheric turbulent diffusion spreads the mist as it propagates away from the source (Csanady, 1971), or 2) in the high-speed jet mixing region, air is sufficiently heated to generate buoyant rise of the water aerosol-heated air mixture within a plume (Briggs, 1969). We hypothesize that possibility (2) is happening, and that the curtain generates a buoyant plume, in which ascent is caused by the development of buoyancy in the water aerosol-air mixture. To test the hypothesis of buoyant plume rise, we measured plume height at times of different river and air temperature for the Horseshoe Falls.

Because of the persistence of flow in the Niagara River and the nearly continuous ability to view and measure, the mist plume provides an excellent opportunity to study certain features of plumes at the natural scale.

Since the time of the visit of Lyell to Niagara Falls in 1841 (Lyell, 1845), earth scientists have shown interest in the river discharge, recession of the falls, and development of Niagara Gorge (Gilbert, 1907; Kindle and Taylor, 1913; Philbrick, 1970; Calkin and Brett, 1978; Tinkler and Pengelly, 1994). Little attention, however, has been paid to the mist curtain that develops at Niagara and at other large waterfalls of the world. In fact, no aspect of the geologic fluid dynamics has been reported on in any detail, despite the existence of a rich phenomenology. In this contribution, we begin to address this shortcoming in our understanding of the hydrodynamics of waterfalls by investigating the generation and rise of the mist curtain and mist plume of Niagara.

MODEL

The idea that we pursue is that the bulk density of the misty air within the mixed aerosol jet, ρ_m, is less than the density of the ambient atmosphere, ρ_a. This condition, $(\rho_m - \rho_a) < 0$, has a chance to occur only if the temperature of the water in the Niagara River is sufficiently high that as the aerosol mixes with ambient air, the expansion of the air heated by aerosol is great enough to cause the bulk density of the mixture to be less than the ambient air density. Thus, if the hypothesis is correct, the plume should be less dense and rise higher on days wherein the temperature difference between river and air is larger.

To conduct a quantitative test of the hypothesis that the mist curtain is a buoyant plume, from Morton et al. (1956), we can make a prediction about plume height for a given temperature difference. Despite the fact that the Niagara plume breaks up into puffs, it reached its maximum rise height before breaking up, thus we assume that the plume is a steady phenomenon for purposes of modeling height of rise:

$$H_T = C_1 N^{-3/4} (C_2 Q_r g (T_m - T_a)/T_a)^{1/4} \quad (1)$$

where, H_T is plume height, C_i (i=1,2) are scaling parameters, C_1

Corresponding Author: M. Bursik
Department of Geology
411 Cooke Hall
University at Buffalo, SUNY
Buffalo, NY 14260
mib@buffalo.edu

Figure 1: Two photographs of Glen Fall, NY, at lower (A) and higher (B) flow rates. At low flow rates, the impact of the falling water on the plunge pool surface is insufficiently powerful to aerosolize the water and form a high-speed jet. At high flow rates, the pressure generated by the impact is sufficiently high to aerosolize water and a high-speed jet is generated.

Figure 2: Photograph of the Niagara Falls atmospheric plume from the seventh floor of the NSC building in Amherst, NY.

characterizing the dependence on potentially important but not explicitly modeled conditions, such as evaporation and condensation (Csanady, 1971), N is atmospheric buoyancy (Brunt-Väisälä) frequency, $Q = C_2 Q_r$ is the flux of aerosolized water that is used to drive plume rise, Q_r being river discharge and C_2 being the fraction of river discharge driven into the mist curtain (assumed fixed), $T_m - T_a = \Delta T$ is temperature difference between mist and air, T_m being mist temperature (it is assumed that $T_m \approx T_r$, the river temperature) and T_a being ambient air temperature, and g is gravitational acceleration. In cases where wind is a significant factor in affecting plume rise, wind speed, u, is taken into consideration. Hence, for buoyancy-dominated plume rise in a windy, stably stratified atmosphere, we can test (Briggs, 1969,Wright, 1984):

$$H_T = C_3\, u^{-1/3}\, N^{-2/3}\, (C_2\, Q_r\, g\, (\Delta T)/T_a)^{1/3} \qquad (2)$$

where C_3 is another scaling parameter.

DATA

The data to be used for model testing consist of measurements of plume rise height (the dependent variable), air and water temperature, atmospheric buoyancy frequency, river discharge and wind speed.

Plume height was measured by photographing or videotaping the plume while at the same time ensuring that the Skylon Tower, Niagara Falls, Ontario, Canada, or another building that could be scaled to the height of the Skylon Tower, was in each frame. All measurements were made from one of two well-located viewpoints, thus viewing geometry was always known (Table 1). The height of the Skylon Tower is 160 m, and, from topographic maps, its base is 4 m above the level of the upper river, which is the lower surface visible in photographic or video frames. Thus we use a total tower height of 164 m above the level of the upper river as a "yardstick". Plume height was found by scaling from this apparent height of the Skylon Tower. For each still frame, taken either from videography or photography, a plume height:Skylon Tower height ratio was measured, and then multiplied by the Skylon Tower height (164 m) to yield the plume height (in meters) (Figure 3).

When using photography, the number of stills varied from five to fifteen, and the single greatest height for plume or puff in each session was used as our estimate of maximum rise height. For videography, a 0.1 Hz sampling rate was chosen as that seemed short enough to illustrate the changes in plume behavior, while being large enough to be economical to work within the allotted work time.

River temperature was estimated to be the same as that recorded for Lake Erie at Buffalo (NOAA, 2002a), near the source of the Niagara River, while air temperature at Niagara Falls was estimated from the temperature at the National Weather Service station in the city of Niagara Falls, NY (Weather Underground, 2002) (Table 1). Atmospheric buoyancy frequency was estimated from low-level radiosonde readings taken at the nearest weather balloon site in Buffalo, NY, using values for times closest to the times of observation of the mist plume (NOAA, 2006). As buoyancy frequency changes slightly over the course of observation, a typical value, representative of all radiosonde readings at appropriate near-surface levels, of $N = 0.015\ s^{-1}$ was used. Data were discarded for the few days during which there was a possibility of low-level temperature inversion at the time of measurement (as indicated by inversions on the day of reading, or adjacent days, if no radiosonde data were taken on a day of observation).

The height of rise of buoyant, environmental plumes should be not only dependent on temperature difference, but also on mass flow rate into the plume. Because this quantity is difficult if not impossible to measure for the Niagara Falls mist plume, we assume that the flow rate into the aerosol jet is proportional to the river discharge (i.e., C_2 = constant). That is, for a higher discharge over the falls, and a constant fraction aerosolized, there will be a higher flow rate of aerosol into the plume. Although flow in the upper Niagara River (above the falls) is quite steady, between the intakes and outlets from the Canadian and American hydroelectric plants, which section includes Niagara Falls, flow varies daily due to hydroelectric extractions. Therefore, because the river discharge can vary greatly during observation, it is critical to consider this variable. The flow rate over the falls (both Horseshoe and American) was estimated from the gauge data recorded at Ashland

Figure 3: A) Photograph from 11/07/2002 of the Horseshoe Falls at low ΔT showing relatively weak plume development. B) Photograph from 01/30/2003 of the Horseshoe Falls at high ΔT showing development of a vigorous buoyant plume. Photographs are from the Sheraton Fallsview Fallscam. The Skylon Tower is off the photographs to the left.

Table 1: Data collection sessions and conditions.

Session	Local Time	T_a (Celsius)	T_w (Celsius)	ΔT	u (kph)	Data Type	Taken From*
1	13:00	2.2	13.3	11.1	14.8	Still	NSC
2	15:00	4.0	12.2	8.2	22.2	Still	NSC
3	15:00	-21.0	0.0	21.0	16.7	Still	NSC
4	18:34	-11.0	0.0	11.0	22.0	Still	NSC
5	16:32	-10.0	0.0	10.0	32.3	Video	Intakes
6	18:04	-10.0	0.0	10.0	27.8	Video	Intakes
7	17:15	9.4	2.2	7.2	20.4	Still	Intakes
8	14:30	3.9	3.9	0.0	33.3	Video	Intakes
9	15:00	-9.4	3.3	12.7	35.4	Still	Intakes
10	16:44	-10.6	3.3	13.9	35.2	Still	NSC
11	16:42	-8.9	2.2	11.1	33.3	Still	NSC
12	9:40	-6.7	0.6	7.3	25.7	Still	Intakes
13	16:23	-4.0	0.6	4.6	20.9	Still	NSC
14	9:25	-18.1	0.0	18.1	15.0	Still	Intakes
15	10:25	-17.1	0.0	17.1	18.5	Still	Intakes
16	10:00	-8.3	0.0	8.3	22.2	Still	Intakes
17	10:45	-1.7	0.0	1.7	46.3	Still	Intakes
18	10:30	-1.7	0.0	1.7	33.3	Still	Intakes
19	11:15	-12.2	0.0	12.2	11.1	Still	Intakes
20	8:45	-13.3	0.0	13.3	13.0	Still	Intakes
21	10:30	-3.9	0.0	3.9	14.8	Still	Intakes
22	18:15	-1.1	0.0	1.1	0.0	Still	Intakes
23	10:00	-2.8	0.0	2.8	0.0	Still	Intakes
24	17:00	-2.2	0.0	2.2	13.0	Still	Intakes
25	10:00	-1.7	0.0	1.7	13.0	Still	Intakes
26	10:45	-7.2	0.0	7.2	22.2	Still	Intakes

"NSC" = Natural Sciences Complex at University at Buffalo.
"Intakes" = Intakes of the New York Power Authority Robert Moses plant along Robert Moses Parkway.
Coordinates: NSC = 43.000625N, 78.792165W
Intakes = 43.076918N, 79.014289W
Approx. center of Niagara Falls horseshoe = 43.078222N, 79.075824W

Avenue, Niagara Falls, NY (Figure 4; NOAA, 2002b). This gauge is just downstream of the falls, and provides the best estimate of the discharge over the falls. Gauge data are given as elevations. The 1964 rating curve for the Ashland Avenue gauge (International Joint Commission, 2007) was used to map the gauge elevation values to discharges:

$$Q_{ri} = 80.282\,(A-290.30)^2 \qquad (3)$$

where Q_{ri} is the flow rate of the Niagara River, given in imperial units (cubic feet per second, cfs), which is then converted to cubic meters per second, and A is the height of the Niagara River at the Ashland Road gauging station, in feet above sea level. It should perhaps be noted that more detailed measurements of discharge at low flow calculated in 1981 and 2007 suggest that the 1964 curve can underestimate discharge by up to about 10%.

The greatest plume height seen throughout the study was 1,107 m, and occurred during Session 3, when ΔT was greatest (ΔT was 21.0 K). Session 14, with the second-highest temperature difference (ΔT was 18.1 K), yielded the second-highest plume, 902 m. This general trend of increasing plume height with increased ΔT measurements was pronounced throughout the dataset (Figure 5).

Puffiness, *i.e.*, the detachment or release of an isolated aerosol cloud from the source, resulting in a sudden drop in plume height, was found to be a typical feature of the mist plume (Figure 6). During Session 8, ΔT was zero (air temperature and water temperature were the same) (Figure 6a). No buoyancy force existed. Puffs therefore exhibited behavior of the mist curtain under the influence only of wind (advection) and turbulence (diffusion). Differences in puff periodicity between measurements in this session and other videographic sessions caused by differences in wind speed (advection) can be neglected, as the wind speed during this session (33.3 kph) was comparable to that during the other two illustrated sessions (32.3 kph and 27.8 kph). The periodicity of puff release was approximately 30 seconds, while the average rise height was about 80 m. In the afternoon, during Session 5, ΔT = 10.0 K, so some buoyancy force existed (Figure 6b). The behavior differed considerably from that in Session 8. The average rise height was

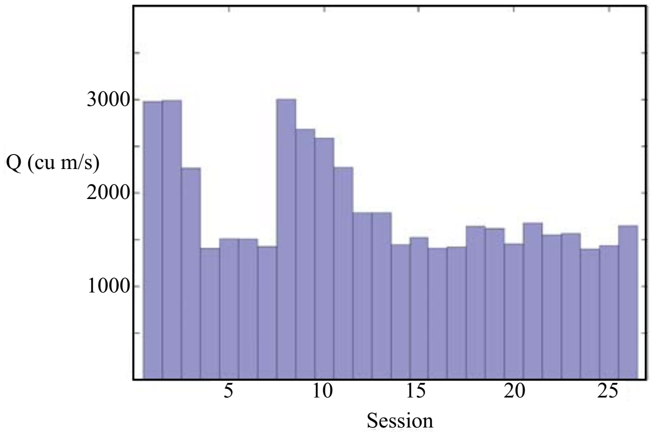

Figure 4: Discharge of the Niagara River at the Ashland Avenue, Niagara Falls, station at the times that plume height data were gathered. We hypothesize that the flux of aerosol into the atmospheric plume is proportional to the flow rate of the Niagara River over the falls.

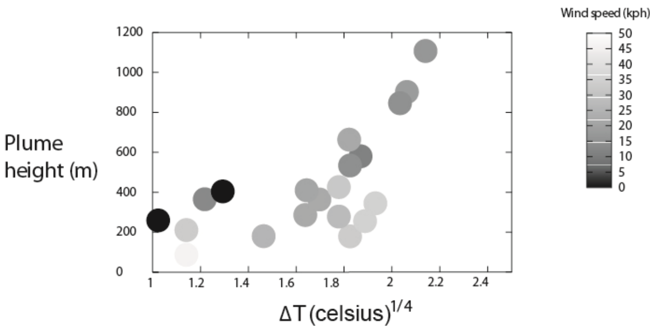

Figure 5: Plume height as a function of estimated water-air temperature difference. In general, plume height increases with increasing temperature difference.

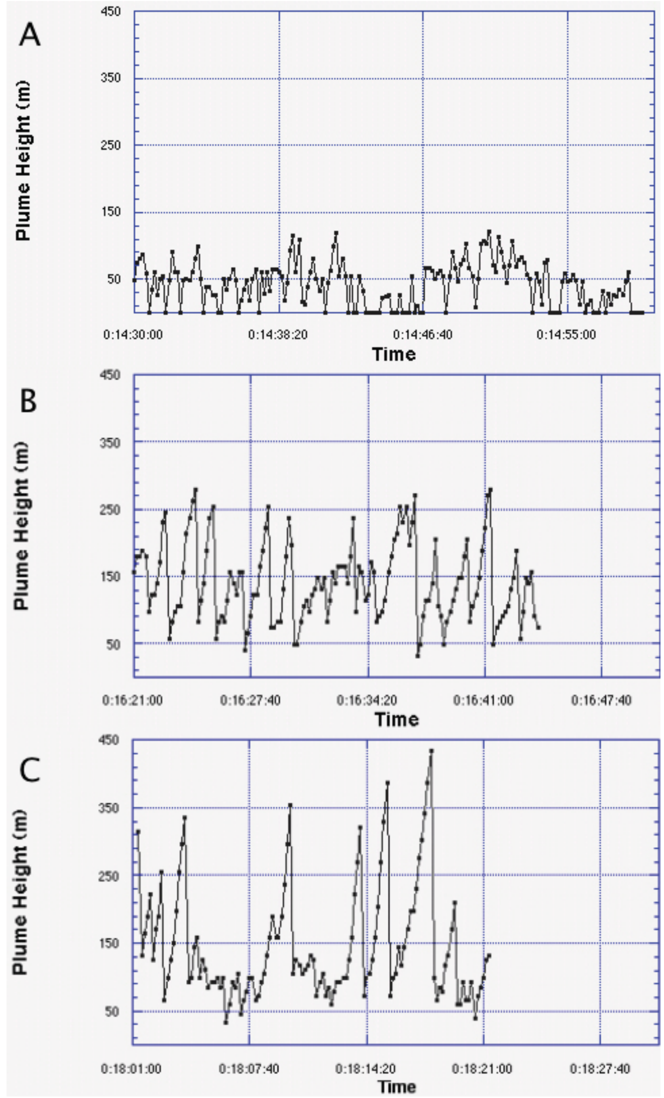

Figure 6: Measurements of plume height at three different times on a 10 s interval. Each sudden, large drop in plume height represents release of a puff. A) Data for 04/17/03, B) Data for 03/10/03 in the afternoon, and C) Data for 03/10/03 in the evening. ΔT in part (A) was lower than that in parts (B) and (C). (C) was measured later in the same day as (B), when wind and atmospheric stratification conditions may have changed.

approximately 250 m, while the highest was 279 m. The periodicity of puff release was different as well, between 1-2 minutes. In the evening, during Session 6, ΔT = 10 K, again, but the plume behaved differently (Fig. 6c). The puffs reached a greater rise height, averaging about 360 m, while the highest reached 433 m. The periodicity was also different, large puffs seemed to be released every 4 minutes, as illustrated in the greatest drops in plume height. These results suggest some modulation by insolation.

ANALYSIS AND INTERPRETATION

Using the data on maximum plume height in a given session, air temperature, water temperature and discharge, we investigated the relationship between plume height and buoyancy flux. The model, Equation 1, suggests that the plume rise height should scale to the 1/4 power of thermal flux. The results are generally consistent with the model (Equation 1; Figure 7a), thus the working hypothesis is supported. The mist plume is largely driven upwards by buoyancy, generated from the mixing of aerosolized warm river water with cold air in the curtain and the high-speed impact jet at the base of the falls. Scatter in the data above a plume height of 200 m is reduced for times during which the wind speed was low (for example, below 25 kph). At and below 100-200 m, plume height does not seem to be a function of buoyancy. This suggests that part of the dispersion in the vertical direction is the result of entrainment of wind into the aerosol curtain as it disperses with little forcing by buoyancy. The scatter is consistent with the notion that wind speed may be the most important explicitly unmodeled variable. To test this hypothesis, we investigated the fit of the model for a plume in an ambient cross flow (Equation 2). The results are consistent with this hypothesis, showing reasonable similarity collapse of the data when wind is considered (Figure 7b), including at and below a 100-200 m rise. Thus, waterfall mist curtains seem to be a type of weak, buoyant plume that is influenced by the wind.

Based on the data from the three videographic records, puff periodicity varies with rise height. The wind speed during all three sessions was comparable (30±3 kph), hence atmospheric entrainment due to wind must be approximately the same for all three sessions. In addition, evaporative cooling of the local air is probably minimal because of the wind induced mixing. Thus, differences among the sessions can be attributed to the variables Q and ΔT, which together determine the total thermal flux. The highest plume (during Session 6), showed the longest period between puff releases. The afternoon Session 5 showed lower rise heights and shorter time between puffs. Session 8 had the lowest puffs and released them on the most frequent basis. This phenomenology is analogous to that seen in experiments of Woods and Caulfield (1992). In both waterfalls and the experiments of Woods and Caulfield (1992), the starting jet from which the plume develops is relatively weak. In the case of waterfalls, this is because momentum is largely directed horizontally; the vertical component is relatively minor. There is insufficient mixing of water and ambient air to generate buoyancy before the vertical component of the jet velocity drops to zero. Within the semicircular Horseshoe, water and ambient air continue to mix, and some of the mixture becomes buoyant. As the buoyant mixture rises, it entrains recently generated and still rapidly flowing jet material, thus remaining attached to the source. When the source thermal flux is high (ΔT and Q large), the plume remains attached for longer and attains a greater height because of maintained attachment. As the source thermal flux diminishes, flow from the source into the plume cannot be maintained as long, and plume height and periodicity decrease. The data from Session 8 were taken when $\Delta T = 0$. In this case there was no buoyancy generation. The puffs were caused by the kinetic energy of the system, most of which was in the ambient atmospheric turbulence. Thus in the limit as $\Delta T \rightarrow 0$, puff formation is rapid and

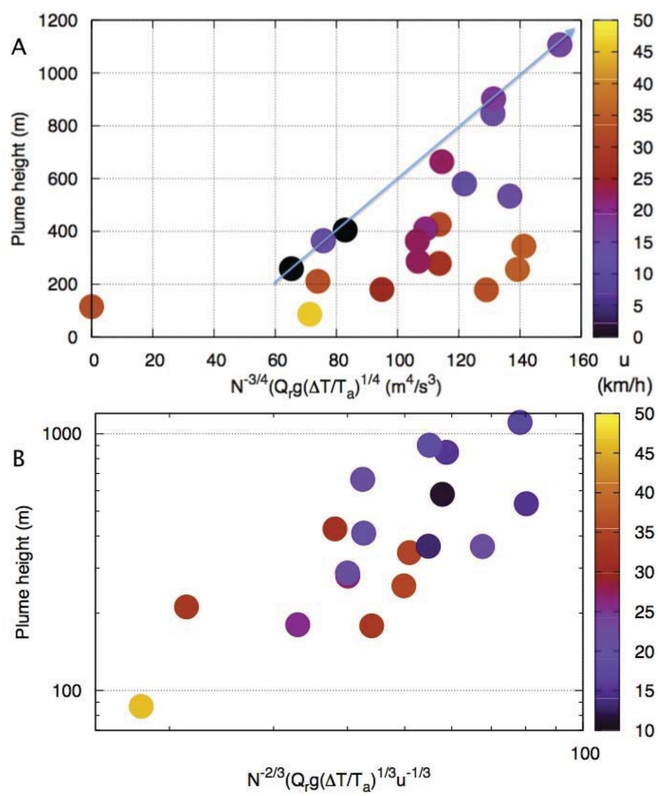

Figure 7: A) Plume height as a function of buoyancy flux and buoyancy frequency. Bouyancy flux is related to heat flux at the source and river discharge; increasing bouyancy flux causes increasing plume height. B) Similarity collapse taking wind into consideration. Increasing wind speed causes decreasing plume height because of the more rapid diluting of plume bouyancy from wind entrainment. In part (A), a characteristic value of $N=0.015\ s^{-1}$ has been chosen, while in part (B) measured values have been used (most of which were close to the characteristic value). In addition, data points for which $\Delta T=0$ or $u=0$ were of necessity removed from the dataset for part (B). Colorbar is wind speed, u, in km/h.

likely caused by the detachment from source of small amounts of nonbuoyant material in the ambient windfield. In all cases, the plume detaches from source near the rise height as material is advected away from source in the wind.

CONCLUSIONS

The results suggest that the mist curtain generated at a great waterfall can gain measurable buoyancy if the water is warmer than ambient atmosphere. In this case, the mixture of waterfall aerosol and air can have a bulk density below that of the ambient, and rise as a buoyant plume. At Niagara Falls, a total rise height of over 1 km has been observed. The Niagara Falls plume always develops a puffy structure, which is consistent with previous experimental results for plumes that do not develop from momentum jets. With higher thermal flux, the period of puff release increases, and there is some indication of additional modulation of periodicity by insolation or other unmodeled parameters. Wind has a major impact on plume behavior, as waterfall plumes are sufficiently weak that they readily entrain horizontal momentum from the wind, and wind should be considered in any future analyses.

Weaknesses in the present effort include wind speed measurements, and other ambient atmospheric measurements, taken from nearby National Weather Service weather stations, rather than taken in situ. Analytic improvements to the present model would include, primarily, incorporation of latent heat release with water phase change, and insolation, explicitly, rather than their simple parameterization.

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