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USE OF THE 1500-pDR FOR GRAVIMETRIC RESPIRABLE DUST MEASUREMENTS AT MINES

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ABSTRACT

The National Institute for Occupational Safety and Health (NIOSH) uses light-scattering dust monitors (nephelometers) in its research to develop dust controls to reduce respirable silica dust overexposures in miners. Recently, the model 1500-pDR, an active nephelometer, was introduced by Thermo Scientific. Testing was completed to ensure compatibility with the metal/nonmetal mine dust personal sampling unit (M/NMDPSU). Results of testing demonstrated that gravimetric concentrations measured from the 1500-pDR are comparable to the gravimetric concentrations measured using the M/NMDPSU, without need for correction, under commonly observed dust loading conditions.

INTRODUCTION

Silicosis is a respiratory occupational disease that has no cure [Porter and Kaplan, 2007]. It is a debilitating occupational disease that often ultimately results in loss of life. Therefore, to prevent the occurrence of silicosis, worker over-exposure to respirable silica dust must be eliminated. Past reviews of the Mine Safety and Health Administration (MSHA) respirable quartz sample database for surface mining have consistently listed the drilling operator as an occupation most commonly impacted by respirable silica over-exposures. However, a recent review of the MSHA respirable silica sample database for surface mining from 1995 to 2009 identifies additional occupations that are also impacted by respirable silica overexposures. Selected occupations impacted are shown in Table 1. Trends for these occupations cannot be identified over this time period due to the differing amount of sampling performed for each occupation. Therefore, only the number of samples >PEL and total samples taken are provided.

The National Institute for Occupational Safety and Health (NIOSH) uses information from the MSHA database considerably to direct dust control research toward areas (based upon occupations) that need it the most. Accordingly, NIOSH develops and tests dust controls that achieve respirable dust reductions to protect mine workers. One of the tools used in dust control research is the light-scattering dust monitor (nephelometer).

NIOSH uses nephelometers extensively in research to develop controls that reduce dust exposures to mine workers. Their ability to provide real-time instantaneous concentrations at specific intervals, which can be user-defined, allows researchers to compare the effectiveness of newly designed controls in mining systems. Additionally, the instantaneous dust concentration readings provide the ability to isolate events that cause dust overexposures to mine workers. Gravimetric dust samplers, while important in mine dust research, provide time-weighted averages (TWAs) over extended time periods, in many cases limiting their ability to establish the success of dust controls.

The most common light-scattering dust monitor used in mining research is the Thermo Scientific Personal Data Ram model 1000 (1000-pDR). It is a passive device where the instrument is set up and records dust concentrations from the surrounding air that infiltrates the instrument's dust chamber. In order to calibrate the 1000-pDR to the type of dust being sampled, gravimetric sampling must be conducted separately. Gravimetric sampling is generally accomplished using a Dorr-Oliver cyclone, 37-mm filter, and a pump operated at 1.7 L/min, commonly referred to as the metal/nonmetal mine dust personal sampling unit (M/NMDPSU).

Table 1. Selected occupations impacted by respirable silica overexposures from 1995 to 2009 based on review of MSHA database.

Occupation	# of Samples >PEL	Total Samples Taken
Metal Mining		
Drill operator	17(11%)	153
Laborer	20(37%)	54
Mechanic	10(21%)	48
Utility man	8(47%)	17
Cleanup man	13(38%)	34
Blaster	1(20%)	5
Sand & Gravel		
Drill operator	4(22%)	18
Laborer	202(20%)	1032
Mechanic	17(11%)	149
Utility man	24(9%)	272
Cleanup man	117(23%)	518
Blaster	0(0%)	0
Stone Quarry		
Drill operator	183(15%)	1247
Laborer	176(14%)	1276
Mechanic	13(8%)	160
Utility man	98(13%)	766
Cleanup man	82(17%)	476
Blaster	3(25%)	12

Note: This list of occupations is not all-inclusive of job categories impacted, i.e., other job categories are impacted but not listed here.
The percentage rates in parentheses should not be used for comparing occupational exposure among the different occupations without considering the total samples taken.
PEL = Personal Exposure Limit.

Recently, Thermo Scientific introduced a redesigned active dust sampling unit—the model 1500 pDR (1500-pDR)—which purports to eliminate the need to conduct secondary gravimetric sampling to calibrate the unit (Figure 1). This is an active device where a pump is used to draw a sample of the surrounding air into the instrument's dust chamber. The device allows for classification of the dust sample before the sampling chamber by integrating a cyclone into the gravimetric collection circuit. The 1500-pDR filter assembly uses a 37-mm filter placed in an open-faced enclosure instead of a sealed unit cassette, which is used with the M/NMDPSU (Figure 2). This configuration results in filter handling requirements that are different from those used with the M/NMDPSU. Specifically, the open-faced enclosure containing the 37-mm filter is vulnerable to potential filter contamination when changing filters outside a controlled atmosphere. Contamination can interfere with filter weights, resulting in incorrect respirable dust concentrations. To help eliminate this vulnerability, care must be taken when changing filters, such as first moving the instrument to a clean area prior to the filters being changed. Additionally, the configuration of the sampling flow path is different from that of the M/NMDPSU, with the respirable dust having to pass through the Dorr-Oliver cyclone, length of tubing, and optical chamber prior to capture on the 37-mm filter.

Figure 1. The 1500-pDR showing the open-faced filter cassette and the location where the filter cassette is attached to the sampling unit.

Figure 2. The open-faced cassette used with the 1500-pDR. The 37-mm filter is placed on the stainless steel backing and the upright ring is pressed onto the filter.

The 1500-pDR had not previously been tested with a Dorr-Oliver cyclone arrangement to ensure compatibility with the M/NMDPSU. Therefore, it was determined that testing was required to verify that the results of the new model 1500-pDR (active) gravimetric 37-mm configuration are equivalent to the current M/NMDPSU commonly used to calibrate the model 1000-pDR (passive).

METHODOLOGY

Testing was conducted using the model 1500-pDR and the M/NMDPSU to compare these gravimetric respirable dust sampling methods for equivalence. Table 2 shows the equipment arrangement used for each sampling type.

All testing was conducted in a Marple chamber using a fine silica dust (5-micron Min-U-Sil, U.S. Silica Co.). The 5-micron Min-U-Sil has the following properties: uncompacted bulk density 36 lb/ft^3, reflectance 93.5, specific gravity 2.65, 6.5 pH, and 96% passing 5 microns [US Silica, 2010]. The Marple chamber is a dust chamber used to provide an atmosphere to the sampling units containing a pre-determined uniform dust concentration. It is located at the Office of Mine Safety and Health Research's lab in Pittsburgh, PA, and has been described in detail in previous publications [Marple and Rubow, 1983; Volkwein et al., 2004].

Table 2. Equipment arrangements for testing gravimetric respirable dust.

	Arrangement 1 1500-pDR	Arrangement 2 M/NMDPSU
Device	1500-pDR	ELF permissible pump or equivalent system*
Cyclone	Dorr-Oliver	Dorr-Oliver
Flow Rate	1.7 L/min	1.7 L/min
Cassette	Open-faced plastic cartridge	Metal/nonmetal SKC Cassette
Filter	SKC 5-micron, 37-mm Part No. 225-8-01	SKC 5-micron, 37-mm Part No. 225-8-01
Backing	Stainless steel screen	SKC provided backing
Tubing Type	Black non-conductive	Black non-conductive
Tubing Length	3 ft.	3 ft.

*Equivalent system described in Methodology section

The test protocol used was based upon previous studies designed to calibrate other dust sampling equipment [Volkwein et al., 2004]. Previous studies were designed to test six instruments along with the six gravimetric samplers. Testing was conducted using five 1500-pDRs and six M/NMDPSUs, as only five 1500-pDRs were available. All 1500-pDR flow rates were calibrated to 1.7 L/min ±5%. The M/NMDPSUs were simulated using a single vacuum pump and six critical orifices calibrated to 1.7 L/min ±5%. This setup allowed for the simultaneous activation of the M/NMDPSUs and is similar to using ELF Escort pumps operated at 1.7 L/min. The duration for each test was 6 hours with dust concentrations tested representative of those commonly measured in the field, ranging from 0.2 to 4.2 mg/m^3. Table 3 shows the randomized target concentrations that were tested. There were a total of 11 tests performed.

To start each test, the six M/NMDPSUs were set up. Their sampling heads included a Dorr-Oliver 10-mm cyclone with a new 37-mm filter in a metal/nonmetal cassette. Each sampling head was connected to the vacuum pump using a critical orifice and 3.0 ft. of conductive tubing. The critical orifice was designed and verified to result in a 1.7 L/min flow rate. Next, the five 1500-pDRs were set up. Their sampling heads consisted only of the Dorr-Oliver 10-mm cyclone which was connected to the instrument using 3.0 ft. of conductive tubing. Setup included zeroing the instrument, placing 37-mm filters into the open-faced cassettes, and installing the cassettes into the side of the samplers. The 1500-pDRs were operated on AC electric power.

All samplers were readied for testing by being placed inside the Marple chamber. Each 1500-pDR was programmed to start at a pre-determined time so that all samplers (including the M/NMDPSUs) could be started simultaneously. The chamber was sealed for testing prior to the sampler start time. A control filter was retained for use during analysis to ensure the integrity of weigh-room procedures, but the filter was not exposed to the test atmosphere.

Once the chamber was sealed, the testing began. The silica dust was slowly introduced into the chamber to allow the dust level to rise to the target dust concentration. Once the target dust concentration was reached, silica dust continued to be introduced to maintain the atmosphere at the target dust concentration. The time to reach the target dust level varied from 1 to 3 hours. The target dust concentration was monitored and maintained using a model 1400 TEOM in conjunction with the Marple chamber. The test ran for 6 hours at which point all the samplers were shut off, and the chamber atmosphere was purged for cleaning and preparation for the next test.

Throughout all testing, the temperature (23.7 to 25.1 degrees Celsius) and relative humidity (47.2 to 52.5%) were relatively consistent. Table rotation in the Marple chamber was maintained in a clockwise/counter-clockwise reversing rotation at the design speed of 1 to 2 revolutions per minute. All filters were weighed before and after testing in the clean room located at NIOSH's Pittsburgh, PA, facility.

Table 3. Dust concentrations in mg/m^3 from testing 1500-pDR and M/NMDPSU. Data are from tests 1 through 6.

Target Concentration (mg/m^3)	TEOM Concentration (mg/m^3)	1500-pDR Instantaneous optical (mg/m^3)	1500-pDR Gravimetric (mg/m^3)	M/NMDPSU Gravimetric (mg/m^3)	Calibration Ratio
Test #1 - 2.60	2.495	1.621	2.459	2.595	1.569
		1.833	2.477	2.492	1.388
		1.896	2.523	2.524	1.341
		1.788	2.399	2.538	1.422
		1.814	2.474	2.557	1.402
				2.552	
Average			2.466	2.543	
Test #2 - 1.40	1.032	0.656	1.056	1.072	1.657
		0.731	1.051	1.088	1.487
		0.742	1.003	1.101	1.466
		0.753	1.031	1.090	1.443
		0.756	1.039	1.082	1.438
				1.090	
Average			1.036	1.087	
Test #3 - 3.00	2.661	1.678	2.662	2.740	1.633
		1.890	2.639	2.730	1.450
		1.991	2.721	2.783	1.376
		1.877	2.557	2.685	1.459
		1.892	2.698	2.752	1.448
				2.747	
Average			2.655	2.739	
Test #4 - 0.60	0.633	0.347	0.605	0.645	1.848
		0.407	0.619	0.652	1.575
		0.417	0.613	0.642	1.540
		0.400	0.611	0.632	1.606
		0.389	0.590	0.640	1.649
				0.637	
Average			0.608	0.642	
Test #5 - 1.00	1.062	0.604	0.969	1.013	1.649
		0.700	0.995	1.064	1.425
		0.725	1.015	1.038	1.375
		0.685	0.948	0.941	1.454
		0.691	0.985	0.958	1.443
				0.969	
Average			0.982	0.997	
Test #6 - 3.80	4.041	2.245	3.642	3.688	1.650
		2.567	3.662	3.680	1.443
		2.637	3.670	3.721	1.404
		2.521	3.516	3.748	1.469
		2.484	3.567	3.742	1.491
				3.645	
Average			3.611	3.704	

The clean room environment is maintained at 22.2 degrees Celsius and 50% relative humidity. The weighing procedure for the filters adhered to the following method. The filters were allowed to desiccate for 30 minutes using a Nalgene Vacuum Chamber. Then the filters were allowed to equilibrate in the clean room for an additional 30 minutes. Immediately following equilibration, each filter was weighed using a Mettler UMX2 micro-balance with the filter being placed upon the microbalance for 1 minute, after which the weight of the filter was obtained.

Filters for the 1500-pDR were pre-weighed and placed in petri dishes for storage until they could be placed into the open-faced cassettes at the time of testing. Filter loading and unloading for the 1500-pDR were conducted outside of the clean room in order to simulate field conditions. After testing, the filters were placed back into the petri dishes until they could be post-weighed. Filters for the M/NMDPSU were pre-weighed and placed in metal/nonmetal cassettes in a clean room. The cassettes remained intact, during and after use, until they were post-weighed in the clean room where the filters were unloaded for post-weighing.

Table 3 (continued). Dust concentrations in mg/m3 from testing 1500-pDR and M/NMDPSU. Data are from tests 7 through 11.

Target Concentration (mg/m^3)	TEOM Concentration (mg/m^3)	1500-pDR Instantaneous optical (mg/m^3)	1500-pDR Gravimetric (mg/m^3)	M/NMDPSU Gravimetric (mg/m^3)	Calibration Ratio
Test #7 - 2.20	2.323	1.258	2.078	2.172	1.74
		1.511	2.198	2.167	1.45
		1.550	2.232	2.168	1.41
		1.490	2.180	2.196	1.47
		1.466	2.194	2.221	1.49
				2.208	
Average			2.176	2.188	
Test #8 - 1.80	1.743	0.959	1.542	1.554	1.37
		1.100	1.528	1.556	1.20
		1.151	1.580	1.547	1.14
		1.107	1.564	1.420	1.19
		1.083	1.577	1.544	1.22
				0.286*	
Average			1.558	1.524	
Test #9 - 4.20	4.060	2.507	3.864	3.974	1.57
		2.865	3.946	3.812	1.38
		2.978	3.917	3.908	1.32
		2.869	3.892	4.044	1.37
		2.792	3.783	3.979	1.41
				3.923	
Average			3.880	3.940	
Test #10 - 0.20	0.201	0.097	0.185	0.208	2.03
		0.113	0.191	0.185	1.74
		0.000**	0.003**	0.190	-
		0.112	0.183	0.191	1.76
		0.110	0.196	0.204	1.79
				0.206	
Average			0.189	0.197	
Test #11 - 3.40	3.418	2.121	3.338	3.408	1.61
		2.442	3.430	3.438	1.40
		2.549	3.438	3.484	1.34
		2.417	3.392	3.322	1.42
		2.381	3.399	3.420	1.44
				3.469	
Average			3.399	3.424	

* Unexplained error, probably due to filter weighing error. This data point was removed from the analysis.

** The 1500-pDR did not operate correctly during this test. These data points were removed from the analysis.

RESULTS

For each of the eleven tests, Table 3 shows the target concentration, the TEOM TWA concentration, the 1500-pDR TWA instantaneous concentration, the 1500-pDR TWA gravimetric concentration, the M/NMDPSU TWA gravimetric concentration, and the calibration ratio. The TEOM TWA concentration, used only to maintain the target dust concentration in the Marple chamber atmosphere, is included for information purposes. No further analysis was conducted with the TEOM data. Analysis was conducted using the other three TWA concentrations and the calibration ratio.

The calibration ratio is used to calibrate the 1500-pDR to the dust type being measured. This procedure is recommended for all light-scattering instruments [Williams and Timko, 1984]. Calibration is accomplished using a gravimetric sampler along with the light-scattering instrument. The ratio is calculated using the following equation:

$$\text{Ratio} = \frac{\text{Grav}}{\text{Instant}} \tag{1}$$

where

Ratio = the calibration ratio

Grav = the gravimetric TWA concentration

Instant = the instantaneous optical TWA concentration from the 1500-pDR.

Next, the calibration ratio is multiplied by each instantaneous optical concentration recorded by the 1500-pDR in order to obtain absolute concentrations. In this analysis, the average of the six M/NMDPSU gravimetric concentrations was used as the gravimetric concentration when calculating the ratio for each 1500-pDR instantaneous optical TWA concentration.

For the linear regression analysis, the average M/NMDPSU gravimetric concentration was used when comparing the M/NMDPSU to both the 1500-pDR instantaneous optical TWA concentration and 1500-pDR gravimetric concentration data. The 1500-pDR data used in the linear regression analysis were the individual concentration data, not averaged as with the M/NMDPSU gravimetric data. The average of the six M/NMDPSU was used because the M/NMPDSU data are the independent variable and the 1500-pDR data are the dependent variable. The independent variable is generally defined to be without uncertainty. When calculating the 95% confidence intervals of the average of the M/NMDPSU gravimetrics, the uncertainty, represented by the confidence intervals, was not found to be excessive. Therefore, using the average as the independent variable was assumed to be reasonable [Williams and Timko, 1984]. Additionally, this method followed previous test protocols [Williams and Timko, 1984] [Organiscak et al., 1988] [Volkwein, 2006].

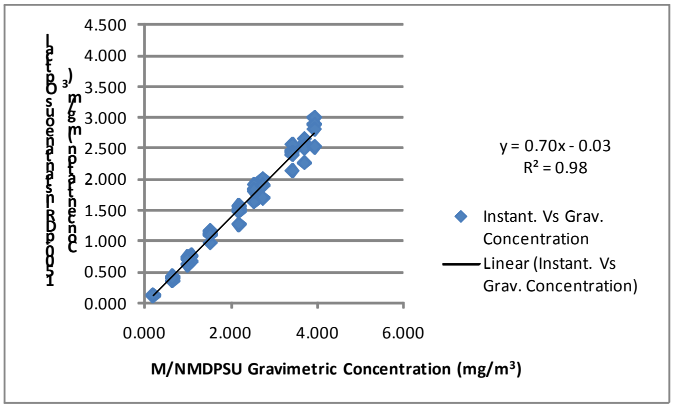

Figure 3, Plot of the M/NMDPSU gravimetric concentrations with the 1500-pDR instantaneous optical concentrations.

COMPARISON OF 1500-PDR OPTICAL CONCENTRATION TO M/NMDPSU GRAVIMETRIC CONCENTRATION

The result of linear regression analysis of the 1500-pDR instantaneous optical TWA concentration as the dependent variable with the gravimetric TWA concentration of the M/NMDPSU as the independent variable is shown in Figure 3. The calculated regression line follows the linear equation format,

$Y = mX + b$:

$$Y = 0.70X - 0.03 \tag{2}$$

This equation has a coefficient of determination or R^2 value equal to 0.98, which demonstrates a strong linear model. In reviewing the linear regression analysis results, the slope (m=0.70) is statistically significant at the 95% confidence interval (0.68, 0.73), with the slope of the regression line differing significantly from zero. The y-intercept (b=0.03) is not statistically significant at the 95% confidence interval (-0.09, 0.02); therefore the null hypothesis that the intercept equals zero is not rejected. Since the slope is less than 1.0, the graph depicts a condition where the 1500-pDR instantaneous optical TWA concentration underestimates the gravimetric TWA concentration of the M/NMDPSU. The inverse of the slope equals 1.42 and can represent an overall acceptable calibration ratio required to correct the instantaneous optical TWA concentrations to the dust type tested (5-micron Min-U-Sil). These results demonstrate that calibration to the dust type being measured is required of the 1500-pDR if absolute concentrations are desired. The strong fit of the data to a linear model indicates that the calibration factor does not change for a range of concentrations that are commonly observed at mine sites.

COMPARISON OF 1500-PDR GRAVIMETRIC CONCENTRATION TO M/NMDPSU GRAVIMETRIC CONCENTRATION

In order to determine if the 1500-pDR gravimetric is comparable to the M/NMDPSU, a linear regression analysis was conducted using the M/NMDPSU gravimetric TWA concentration as the independent variable and the 1500-pDR gravimetric TWA concentration as the dependent variable [Organiscak et al., 1988]. The graph in Figure 4 shows the plot of the data.

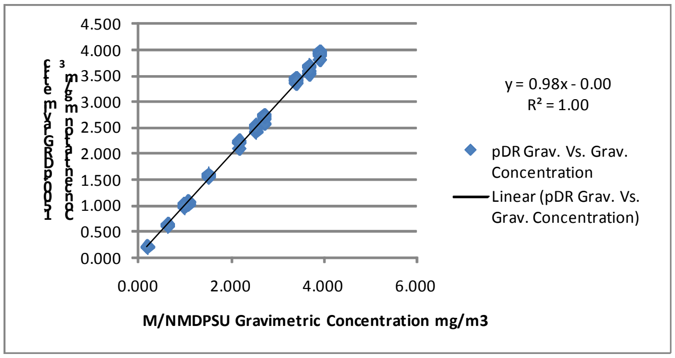

Figure 4. Plot of M/NMDPSU gravimetric concentration with the 1500-pDR gravimetric concentration.

The calculated regression line is shown:

$$Y = 0.98X - 0.00 \tag{3}$$

This equation has an R^2 value equal to 1.00, which demonstrates a strong linear model. In reviewing the linear regression analysis results, the slope (m=0.98) is statistically significant at the 95% confidence interval (0.97, 1.00), with the slope of the regression line differing significantly from zero. The y-intercept (b=0.00) is essentially zero with the 95% confidence interval (-0.03, 0.02). Because the slope is close to 1.0 and the intercept is not statistically significant (i.e., the null hypothesis that the intercept equals zero is not rejected) and tightly grouped (95% confidence interval) around zero, the gravimetric concentrations measured from the 1500-pDR are comparable, without need for correction, to the gravimetric concentrations measured with the M/NMDPSU. In other words, the 1500-pDR gravimetric is satisfactory for calibrating the instrument to the dust type being measured.

CONCLUSIONS AND RECOMMENDATIONS

The results of this testing show that instantaneous concentrations from the 1500-pDR underestimate the gravimetric concentrations and require calibration in order to obtain absolute concentrations for the dust type being measured. The overall calibration ratio calculated (using slope in Figure 3) in this testing, using 5-micron Min-U-Sil, was 1.42. This correction factor was consistent over a range of concentrations that are commonly observed at mine sites.

It should be noted that the 1500-pDR may not always underestimate the gravimetric concentrations. Whether it overestimates or underestimates gravimetric concentrations will be dependent upon the characteristics of the dust type being measured, as light-scattering instrument results are dependent upon the particle characteristics (size, surface reflectance, and index of refraction) [Williams and Timko, 1984]. Calibration of a light-scattering instrument using a gravimetric instrument has always been recommended in order to obtain absolute measurements. However, this does not preclude the use of the 1500-pDR for gathering relative measurements.

The gravimetric concentrations measured using the 1500-pDR are comparable to the gravimetric concentrations measured using the M/NMDPSU without need for correction under commonly observed dust loading conditions. The results show that the M/NMDPSU is not required alongside the 1500-pDR to obtain gravimetric concentrations. The 1500-pDR gravimetric measurements are sufficient and can be used for calibrating the 1500-pDR. As a research tool, the 1500-pDR is a suitable alternative for respirable mine dust sampling when compared to a pDR-1000 used in conjunction with the M/NMDPSU.

There are some important points to consider that will augment the hypothesis that the 1500-pDR gravimetric concentrations are comparable to the M/NMDPSU gravimetric concentrations.

The filters used in the 1500-pDR should be the same as those for the M/NMDPSU, which uses a 5-micron PVC filter.

When handling the filters for the 1500-pDR, extreme care must be taken to not contaminate the filter. This includes using tweezers to handle the filter and changing the filter in an area that is relatively dust-free.

It is best to have extra cartridges (Figure 2) and have the filters pre-weighed, inserted into the cartridge, and stored in petri dishes prior to testing.

Once testing is to occur, the cartridge should be inserted just prior to testing in a relatively clean area.

Once testing is completed, the unit should be removed to a relatively clean area and the cartridge replaced, with the used filter (cartridge and all) placed into a petri dish for storage until the filter is removed for weighing.

Assuming that the above procedures are followed, the 1500-pDR can provide TWA respirable dust concentrations that are comparable to the gravimetric concentrations measured using the M/NMDPSU. This would eliminate the need for the M/NMDPSU to be used alongside the 1500-pDR to obtain gravimetric concentrations.

DISCLAIMER

Mention of any company or product name does not imply endorsement of that product by NIOSH. The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the NIOSH.

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