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MODIFICATION OF FLUX PROFILES USING A FACETED CONCENTRATOR

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ABSTRACT

The use of a faceted solar concentrator allows for some flexibility in aiming strategy and in the intensity of the resulting flux profile at the target. This can be an advantage when considering applications that do not necessarily require maximum concentration, particularly emerging, new applications in solar processed advanced materials. This paper will describe both an analysis of predicted flux profiles for several different aiming strategies using the SOLFUR computer code and experiments to characterize the actual flux profiles realized with a selected aiming strategy. The SOLFUR code models each of the furnace components explicitly. Aim points for each facet can be specified. Thus many strategies for adjusting aim points can be easily explored. One strategy calls for creating as uniform a flux over as large an area as possible. We explored this strategy analytically and experimentally. The experimental data consist of flux maps generated by a video imaging system calibrated against absolute flux measurements taken with circular foil calorimeters. Results from the analytical study and a comparison with the experimental data indicate that uniform profiles can be produced over fairly large areas.

1. INTRODUCTION

The use of a faceted solar concentrator allows for some flexibility in aiming strategy and in the intensity of the resulting flux profile at the target. This can be an advantage when considering applications that do not necessarily require maximum concentration. Typically, solar concentrators are designed to deliver maximum flux. This is entirely appropriate for those thermal applications in which optimizing energy efficiency is important. There are a growing number of applications, primarily in advanced materials processing, in which other considerations will drive the solar concentrator design. These considerations include expanding the target area at a specified flux to increase the production rate, enhancing the ability to control the process, and making the design flexible to adapt quickly to changing process/product requirements. As solar-processed-materials technology matures, the ability to deliver large areas of controlled, concentrated flux will play a major part in the commercial success of the technology. Because of the geometric nature of the problem, the experiments described here should scale readily to larger industrial-scale production facilities.

Many of these new applications can take advantage of a solar furnace with a faceted concentrator design. A solar furnace is distinguished from other concentrator concepts in that the target point or working area is fixed at or near ground level. The National Renewable Energy Laboratory (NREL) operates a unique solar furnace to explore new applications of concentrated sunlight. This facility, the High-Flux Solar Furnace (HFSF), has a multi-facet primary concentrator that can easily modify the flux profile at the target. The basic design and layout of the facility is shown in Fig. 1.

The HFSF at NREL is unique among solar furnaces (1). The 31.8-m^2 flat heliostat tracks the sun and directs the rays onto the primary concentrator. The HFSF uses a fixed, multifaceted 12.5-m^2 primary concentrator with a focal-length-to-diameter (f/D) ratio of 1.85. The primary concentrator consists of 25 hexagonal facets or mirrors. Each facet is 762 mm across the flats, ground and polished to a spherical curvature with a radius of 14.6 m, and coated with a UV-enhanced front-surface aluminum reflective layer. Each facet can be individually aimed using a three-point, adjustable mounting fixture. The primary concentrator redirects the flux 30^o off-axis

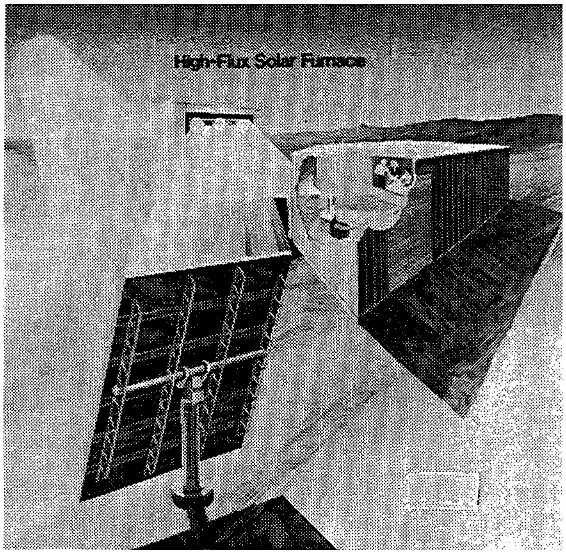

Fig 1. NREL's High-Flux Solar Furnace.

through an attenuator, which controls the level of flux at the target. This unique off-axis design allows the experiment to be located outside the beam between the heliostat and the primary concentrator. An air-actuated, actively cooled shutter is located in front of the focal point. The experiment (or target) sits atop a three-axis XYZ positioner.

With the standard configuration, peak fluxes in excess of 2500 kW/m^2 have been measured over a 2.5-cm diameter circle, resulting in concentrations of more than 2500 suns (2). Ninety percent of the flux is contained within a circle 10.1 cm in diameter, with a peak-to-average-flux ratio of 2.1:1. The high f/D of 1.85 (most dish concentrators at existing solar furnaces have an f/D ~ 0.6) was designed to take advantage of nonimaging secondary concentrators developed by the University of Chicago (3). With a reflective compound parabolic secondary concentrator, we have attained average concentrations of more than 20,000 suns over a 1.5-cm diameter exit aperture. Concentrations of 50,000 suns are expected with a refractive secondary currently being tested.

Experiments performed to date include numerous materials surface processing tests, including surface hardening, cladding, diamond film growth, superconductor coatings, and metallization of ceramics (4). Other tests include production of ceramic powders, photochemical detoxification of trichloroethylene and dichlorobenze, and thermal flash effects of nuclear weapons. Using concentrated sunlight for many materials-related applications allows the system to be scaled to the specific needs of a given application. We chose to explore this feature with a series of experiments

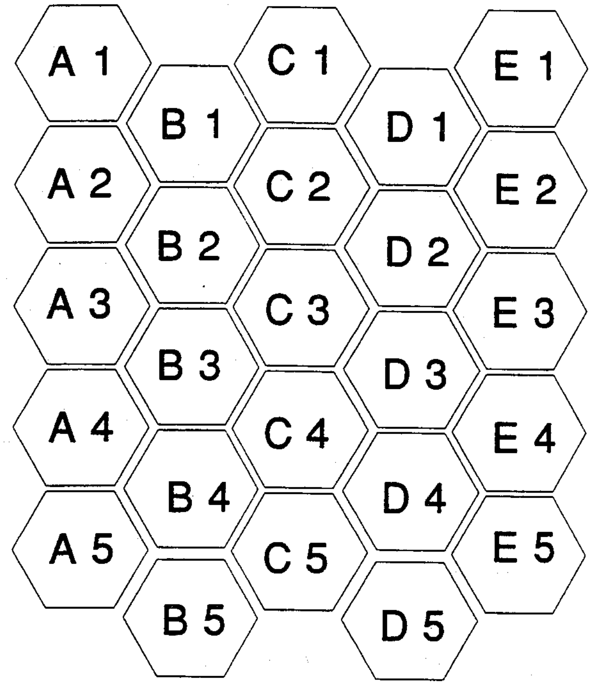

Fig. 2. Layout and identification of facet at the HFSF.

and corresponding analytical predictions to determine the HFSF's ability to deliver a more uniform flux profile.Many of our materials processing experiments use square, flat targets with 5-cm-long sides. Targets of this size and slightly larger represent what we consider to be the size of near-term commercial-size workpieces. Although a uniform flux profile has many advantages for most materials processing applications, the level of uniformity required for these applications remains unknown. With further development, specific requirements for the concentrated solar flux delivered to these materials applications will be defined.

2. ANALYSIS

The SOLFUR computer code models the HFSF configuration explicitly, using a ray-trace method. Results of the code show excellent agreement with experiments (5). Because the code can assign an individual aim point to each of the 25 facets, almost any type of aiming strategy can be easily explored (Fig. 2 shows the primary facet layout with facet identifiers). Our objective was to determine the level of flux profile uniformity we could attain with several possible aiming strategies. We chose to explore analytically both a hexagonal and square aim point strategy.

The hexagonal pattern seems intuitively to offer the best approach. We modeled a seven-facet array with various aim point separations. The seven aim points were

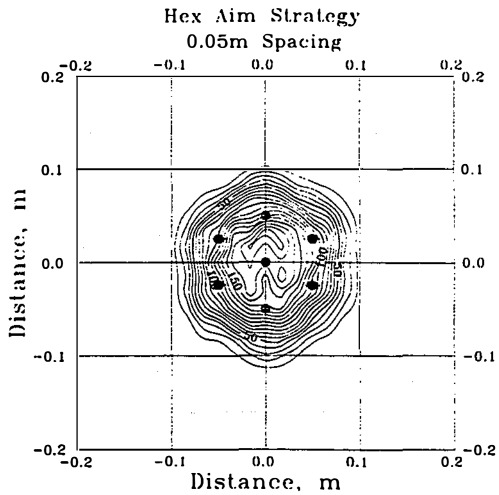

Fig. 3. Analysis results for hexagonal spacing of 5 cm. Flux in kW/m^2. Contour intervals: 10 kW/m^2.

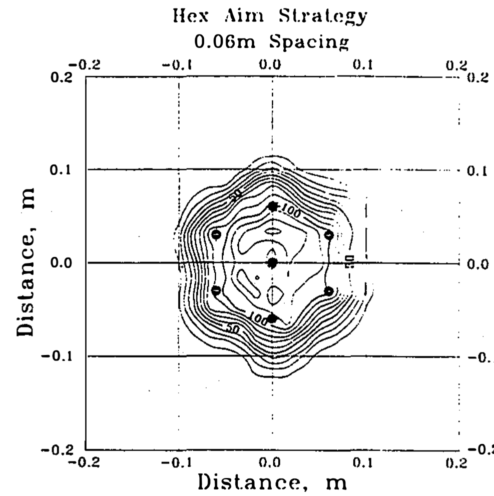

Fig. 4. Analysis results for hexagonal spacing of 6 cm. Flux in kW/m^2. Contour intervals: 10 kW/m^2.

arranged in a central column of three centered on the optical axis and two additional columns of two on either side. The seven central facets of the primary array were assigned aim points in the SOLFUR input files. The initial analysis used facets B2, B3, C2, C3, C4, D2 and D3. Using the nominal HFSF optical error, reflectivity values and a direct irradiance of 950 W/m^2, the analysis generated results for hexagonal aim point spacings of 5, 6 and 7 cm. Contour plots of these results are shown in Figs 3-5 with the aim points added to the plot. These results indicate that a somewhat flatter profile begins to form at a 5-cm spacing and begins to separate into individual facet images at the 7-cm spacing. The flat portion of the profiles tend to have flux values around 100 kW/m^2 which represents the maximum for any given individual facet.

The square pattern was also modeled. In this case, there were three columns of three aim points. The central column again was centered on the optical axis. The nine facets used for this strategy were: B2, B3, B4, C2, C3, C4, D2, D3 and D4. The same three spacing values of 5, 6, and 7 cm were used in the model. The analytical results for the square strategy are shown in Figs. 6-8. For these runs, the profile flattening seems to occur at somewhat lower spacing values than the hexagonal, probably because the aim points are not packed as well.

In both the hexagonal and square strategies, the 6-cm spacing seems to create the "best" uniformity over the largest area. In both cases, an area that corresponds to approximately 10 cm in linear dimension gives the appearance of reasonably uniform flux. In order to determine whether this could be achieved in practice, we

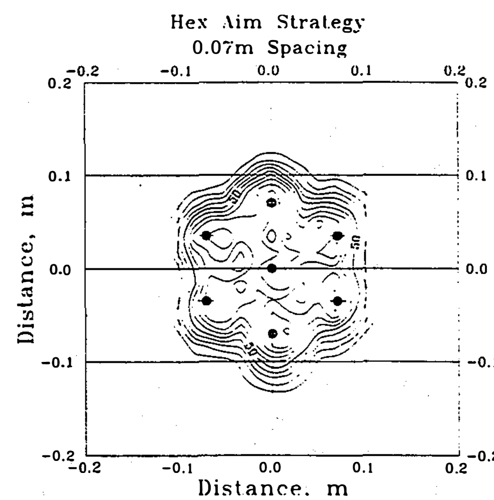

Fig. 5. Analysis results for hexagonal spacing of 7 cm. Flux in kW/m^2. Contour intervals: 10 kW/m^2.

conducted several experiments at the HFSF using both strategies at an aim-point spacing of 6 cm.

3. EXPERIMENTS

Facet alignment targets for both the hexagonal and square patterns were made from rigid, high-temperature insulation boards with metal tacks placed at the desired facet aim-point spacing of 6 cm. The targets were placed at the nominal focal point of the furnace, perpendicular to the furnace's optical axis.

A solid-state array video camera, focused on the target, was used to visually aim the concentrator facets. We

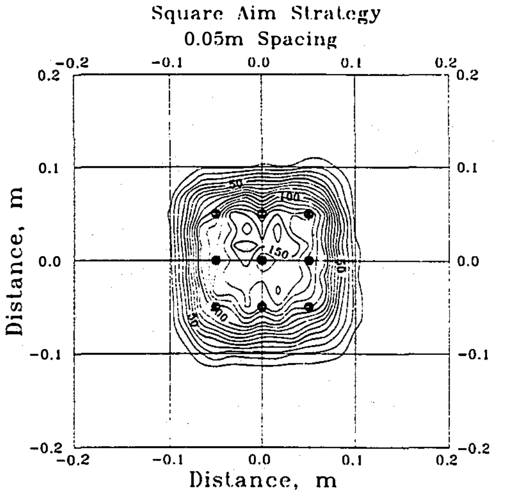

Fig. 6. Analysis results for square spacing of 5 cm. Flux in kW/m^2. Contour intervals: 10 kW/m^2.

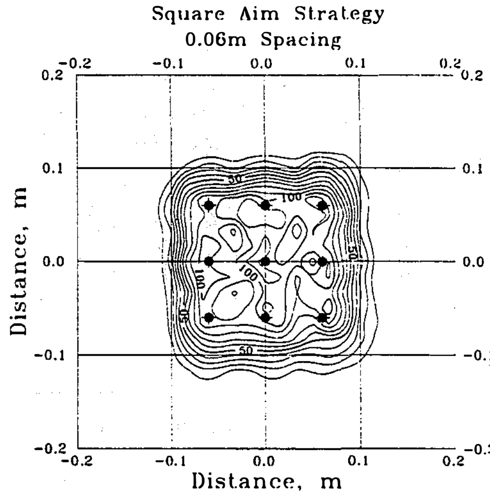

Fig. 7. Analysis results for square spacing of 6 cm. Flux in kW/m^2. Contour intervals: 10 kW/m^2.

used a PC-based laser diagnostic software and hardware system called BEAMCODE to produce real-time, pseudo-color images from the video camera that can be captured and analyzed. Because each facet's image has a Gaussian-like profile with a clearly distinguished peak, it is relatively easy to individually position each concentrator facet to its desired point on the target.

To determine the uniformity of the flux profiles, we placed a flux mapping plate at the focal point of the furnace. The flux mapper uses a black and white video camera and frame grabber in conjunction with the BEAMCODE software package for flux distribution analysis. The flux measurements with the calorimeters and the flux profiles with BEAMCODE are taken from a single actively cooled plate Along one side of the front surface of the plate is a vertical array of seven actively cooled circular foil calorimeters. The remainder of the front surface is a uniformly diffuse white surface from which the flux map is obtained. The location of the calorimeters next to the flux mapping area allows the calorimeters to be precisely positioned after we take a flux map so that a corresponding measurement of flux can be obtained. The calorimeter measurements provide reference points from which a computer-generated color image of intensity can be scaled.

Because an unusual local deformation in the heliostat that illuminates the central facet (C3), we assigned facet E3 to the central aim point. The image from C3 was distorted from the nominal, slightly elliptical image typical of all other facets and tended to adversely affect the uniformity of the overall profile. Modelling of this facet

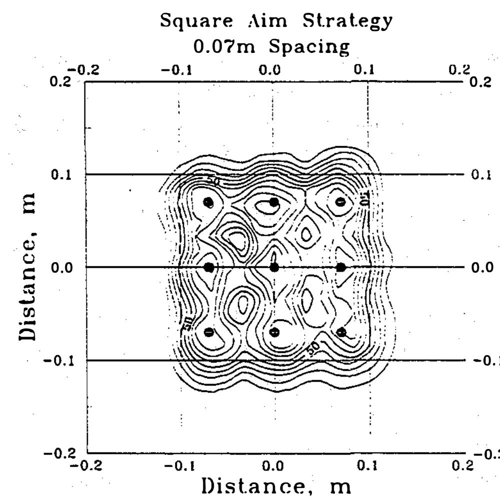

Fig. 8. Analysis results for square spacing of 7 cm. Flux in kW/m^2. Contour intervals: 10 kW/m^2.

reassignment indicated no measurable affect on the resulting flux profile.

After this change, BEAMCODE images of the two aiming strategies were captured with the flux mapping plate placed at the focal point and, for the square pattern an additional image was captured 2 cm behind the focal point. The data from these images were scaled using the calorimeter data as described above and then transformed into a format to display as a contour plot. These plots are shown in Figs. 9 and 10 for the focal plane images.

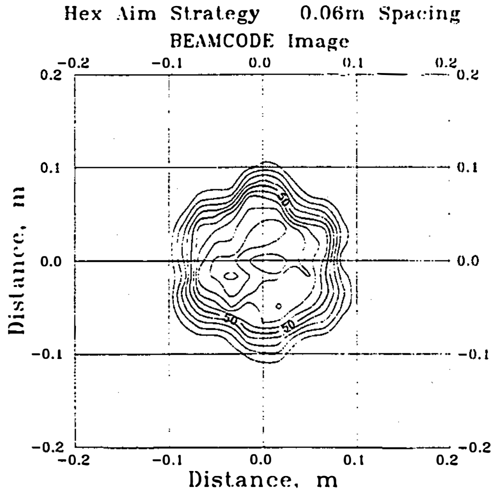

Fig. 9. Captured image of hexagonal spacing of 6 cm. Flux in kW/m^2. Contour intervals: 10 kW/m^2.

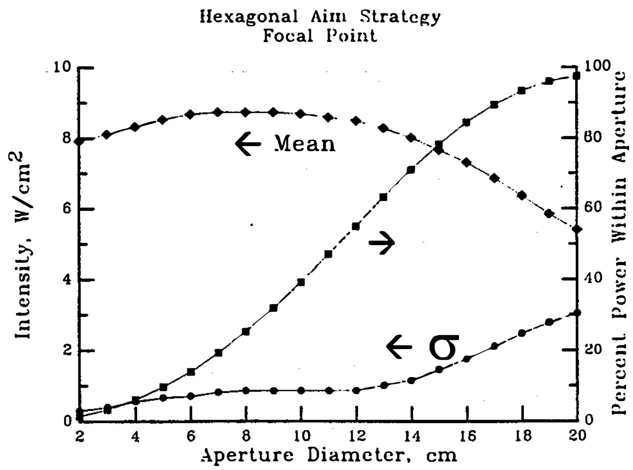

Fig. 11. Image analysis of hexagonal spacing of 6 cm.

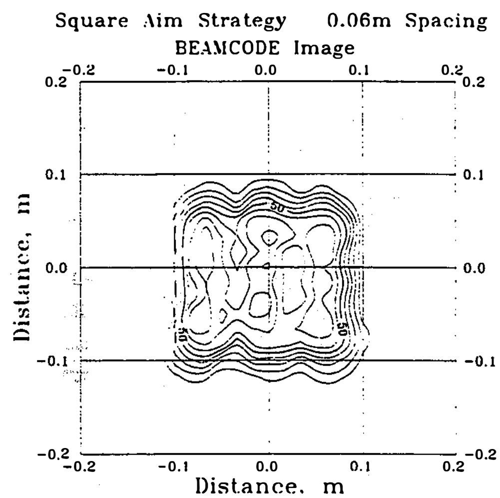

Fig. 10. Captured image of square spacing of 6 cm. Flux in kW/m^2. Contour intervals: 10 kW/m^2.

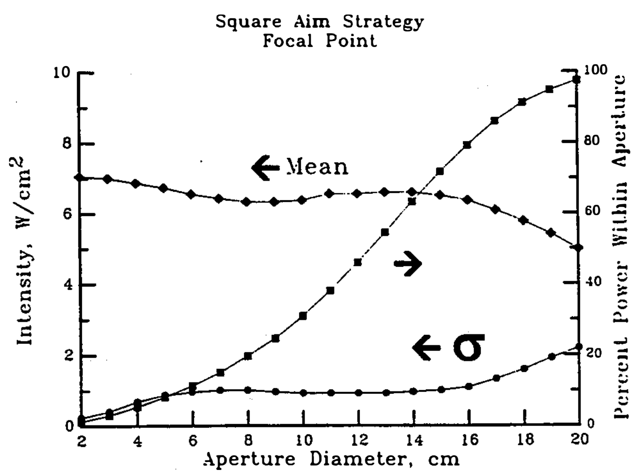

Fig. 12. Image analysis of square spacing of 6 cm.

4. DISCUSSION OF RESULTS

The BEAMCODE software analyzed images for uniformity and variation for various aperture sizes and shapes. This analysis yielded some very encouraging results for the three images described in the previous paragraph. At each aperture size the percent power, we calculated mean intensity and standard deviation of intensity.

The hexagonal strategy image was analyzed using a circular aperture centered on the centroid. The centroid is located very close to the optical axis. Aperture diameters as high as 20 cm encompassed nearly the entire image. Figure 11 shows that for apertures of about 5-12 cm in diameter both the mean intensity and standard deviation remain quite constant with the standard deviation at about 1/10 of the mean. This indicates that some variation exists but may be acceptably small for many experiments.

For the square strategy images, a square aperture centered on the centroid was used. The image taken at the focal point yields a slightly larger uniform image. Image analysis results are shown in Fig. 12. Here the uniform area corresponds to a square with sides of between 5-14 cm with a somewhat higher ratio of standard deviation to mean than for the hexagonal image. This result can be understood based on the aim point packing for this strategy, which can yield "holes" in the areas centered between aim points.

The image taken using the square strategy at 2 cm behind the focal point yielded more acceptable results than that at the focal point. The data, shown in Fig. 13, indicate a lower standard-deviation-to-mean ratio compared with the focal point data for this strategy. This represents a more uniform image. These changes were much more obvious during the experiments when viewing the real-time monitor of the image. In addition, more uniform images were possible by using the targets to determine the nominal facet aim points and then making minute changes in the positioning of individual facets.

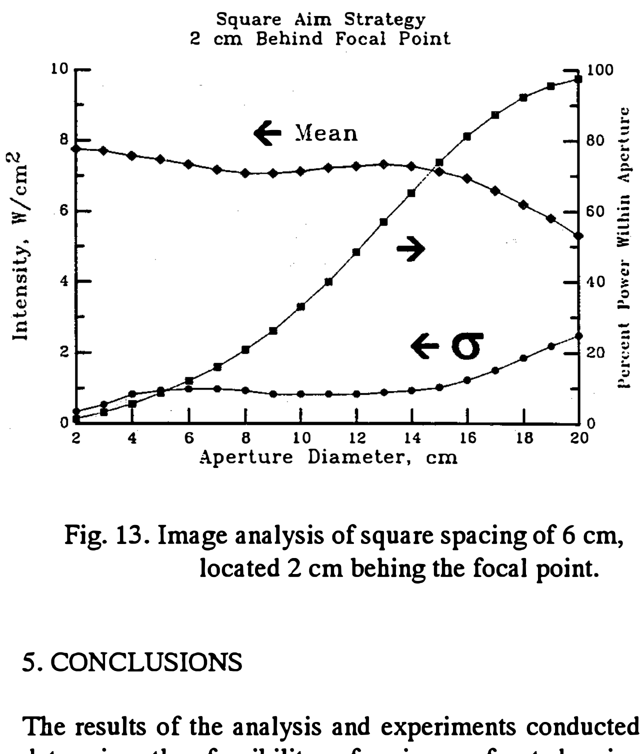

Fig. 13. Image analysis of square spacing of 6 cm, located 2 cm behing the focal point.

5. CONCLUSIONS

The results of the analysis and experiments conducted to determine the feasibility of using a faceted primary concentrator to produce a uniform flux profile have yielded highly encouraging results. The HFSF can be used to generate relatively uniform profiles of up to 14 cm across with the strategies described. At mean intensities of 70-90 kW/m^2 (concentrations of around 100 for these experiments) many current and future experiments can better demonstrate commercial potential. Opportunities exist to improve both the uniformity and intensity of the resulting profiles. For example, more facets could be used with aim points in-between those of the strategies used here. A concentrator with smaller facets may be able to reduce the variation in intensity over a given area.

In the near-future, many experiments conducted at the HFSF in materials processing technologies will use the strategies examined here. This should result in more consistent, better performing, and larger materials that are more representative of commercial-scale products. As industry interest in this technology grows, we expect that commercial-scale systems will take full advantage of the capabilities of faceted concentrators to deliver the specific flux levels and distributions required by the particular materials processes.

6. ACKNOWLEDGMENT

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