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***In-situ* surface debris inspection and removal system for upward-facing transport mirrors of the National Ignition Facility**

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ABSTRACT

We describe a system to inspect and remove surface debris *in-situ* from the surfaces of upward-facing mirrors that transport 1053 nm laser light to the target chamber of the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory. Grazing angle ($2-5^\circ$) illumination with a bar light highlights debris $\approx 10\text{ }\mu\text{m}$ in size and larger, which is then viewed through windows in the enclosures of selected mirrors. Debris is removed with 1-second bursts of high velocity (76 m/s) clean air delivered across the optic surfaces by a commercially available linear nozzle (“gas knife”). Experiments with aluminum, stainless steel, glass and polystyrene particles of various sizes $>30\text{ }\mu\text{m}$ show that particle removal efficiency is near 100% over most of the mirror surfaces for all sizes tested.

Keywords: Surface debris removal, gas knife, mirror surface cleaning, NIF

1. INTRODUCTION

Surface debris is known to be a contributor to local surface damage on mirrors used in high power lasers. Removing such debris and maintaining a high degree of cleanliness are therefore of paramount importance to prolonging the life and performance of laser optics. The transport mirrors of the National Ignition Facility (NIF) of the Lawrence Livermore National Laboratory, direct 1053 nm (“ 1ω ”) light from the main amplifiers to the target chamber, and form the final critical link in the beam path (Figure 1). These mirrors, which are 44 cm x 69 cm (17.4” x 27.3”) in size, are currently used at a fluence of approximately 9 J/cm^2 , but future operating conditions are likely to require that they sustain fluences of 16 J/cm^2 or more. Under such conditions rigorous cleanliness is critical to prevent damage to the mirror surfaces and prolong the life of these optics.

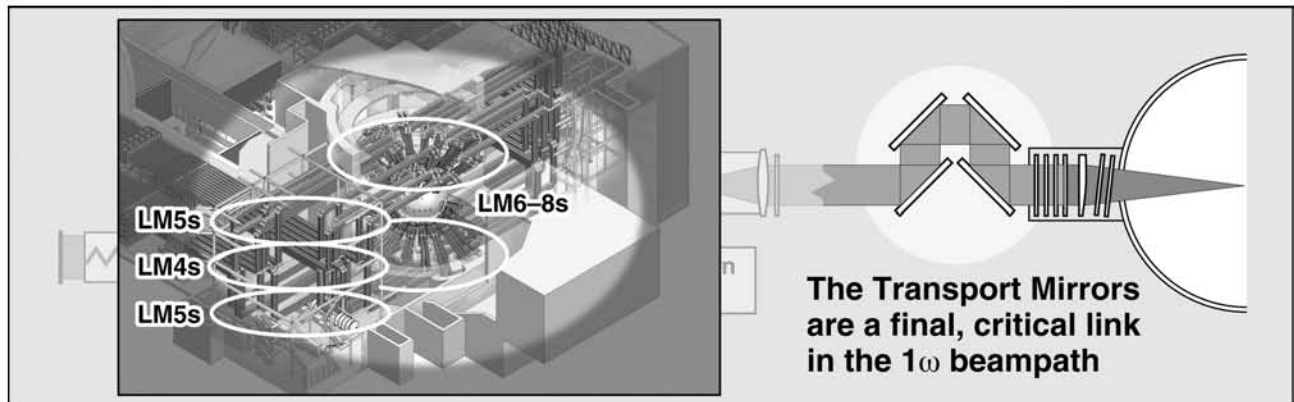


Figure 1: Placement of the transport mirrors on the NIF. The physical locations are indicated in the drawing at left and the placement in the beam path is indicated schematically on the right (inside the light gray circle, center right).

Upward-facing mirror surfaces are clearly the principal concern. Not only do dust and other light debris gradually settle on these mirrors, but they are also the targets of heavy debris that might fall from above. Particulate debris has been

found within the enclosures of the NIF transport mirrors, and consists of metal fragments, mineral particles and organic fibers (Figure 2). An inspection in October 2003 indicated that an average of 52 (range: 23-85) particles $\geq 50 \mu\text{m}$ in diameter and an average of 8 (range: 5-10) fibers of all lengths had deposited on each of four LM5 mirrors after being inside the enclosure for about eight months. There are 288 upward facing transport mirrors on the NIF, ninety-six each of Laser Mirrors (LM) 4, 5 (Figure 3) and 8 (Figure 4). Although each category of mirror performs the same function within the NIF beam path, as the drawings in Figure 3 and 4 suggest, the individual installation configurations vary. Furthermore, congestion in parts of the structure makes frequent access to the mirrors difficult, especially around the target chamber (Figure 4). Removing each of the ninety-six upward-facing mirror assemblies (termed “line replaceable units” or “LRUs”) is a time consuming and costly operation that requires extensive preparations and more than twenty-five hours of labor per LRU (Figure 5). Such time-intensive operations would likely have a detrimental impact on the NIF shot schedule. Removal also places the mirrors at risk of damage from the hazards associated with the handling of any optic, even those that are well protected. Removal of LRUs for regular inspection and cleaning is therefore not an attractive option for maintaining mirror cleanliness. In this paper we describe a system that allows mirrors to be inspected *in-situ* for the presence of surface debris as small as $10 \mu\text{m}$ in size and removes the debris *in-situ* using a high speed sheet of air blown over the mirror surface.

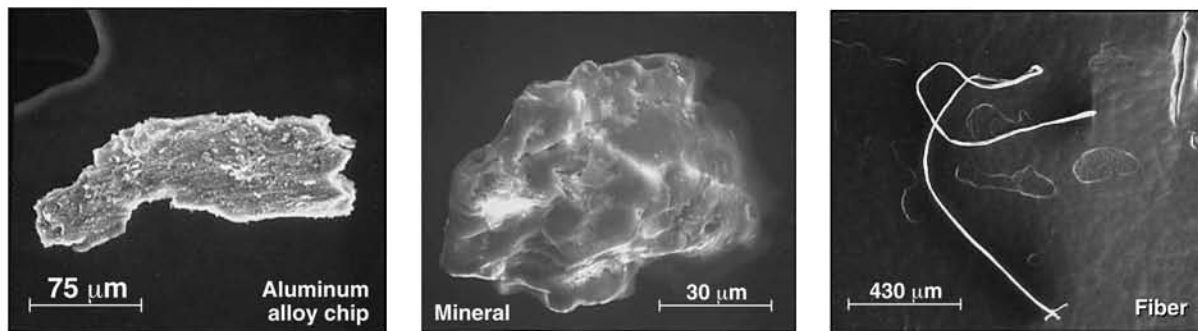


Figure 2: Examples of debris found in NIF beam path enclosures.

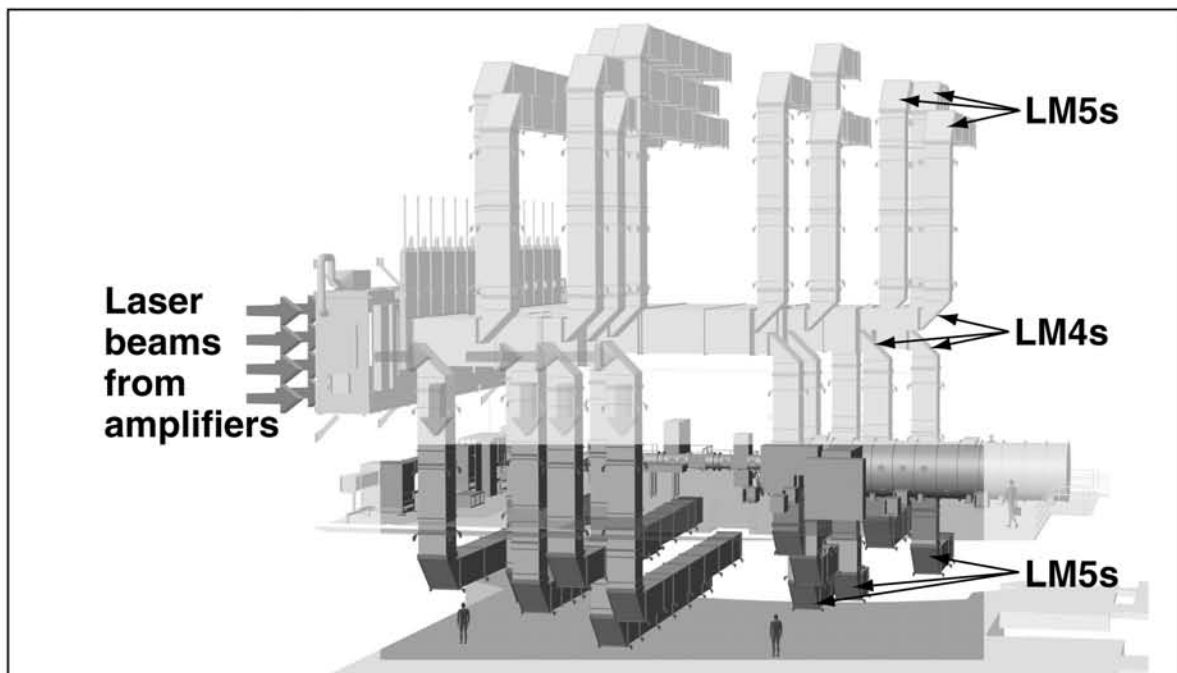


Figure 3: Illustration of the positions of LM4 and LM5 mirrors in the “switchyard” section of the NIF between the main amplifiers and the target chamber.

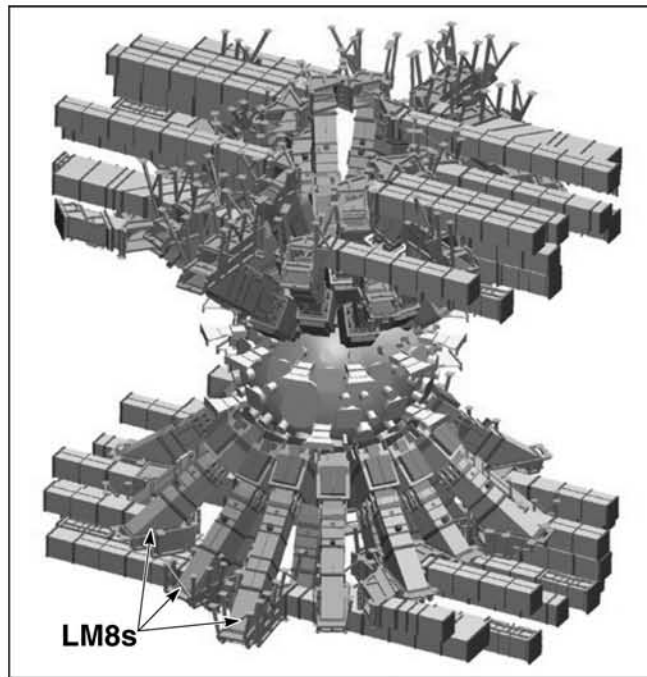


Figure 4: Illustration of the positions of the LM8 mirrors around the NIF target chamber.



Figure 5: Removal of an LM5 LRU. Local cleaning requires the construction of local clean rooms in areas, which can be very congested.

2. EXPERIMENTAL

The transport mirrors of the NIF are surrounded by elbow enclosures, an example of which is shown installed in the beam path in Figure 6. The mirror assembly (LRU) consists of a heavy stainless steel frame on which four mirrors are mounted inside of two smaller enclosures or “tubs” that mate and seal against the frame of the elbow enclosure as illustrated in Figure 7. To highlight particulate debris, we have designed a system that provides grazing-angle (2-5°) illumination of mirror surfaces by means of a bar light conveniently mounted on upper and lower rims of the mirror tubs (Figure 7). The bar light¹, Figure 8, uses bundled fiber optics and a cylindrical lens to deliver uniform, intense white light across the width of each mirror. To view the scattered light *in-situ*, we have designed windows on the walls of the elbow enclosure that allow direct viewing of light scattered by surface debris normal to the illumination direction at an elevation of 20-30°. The unaided eye is extremely adept at detecting and assessing fine surface debris under these viewing conditions. Experiments with sized powders have demonstrated that debris as small as 10 µm can be easily observed. A view of an illuminated LM5 mirror through a viewing window is shown in the photograph of Figure 9.



Figure 6: An LM5 upward-facing elbow enclosure installed in the NIF beam path.

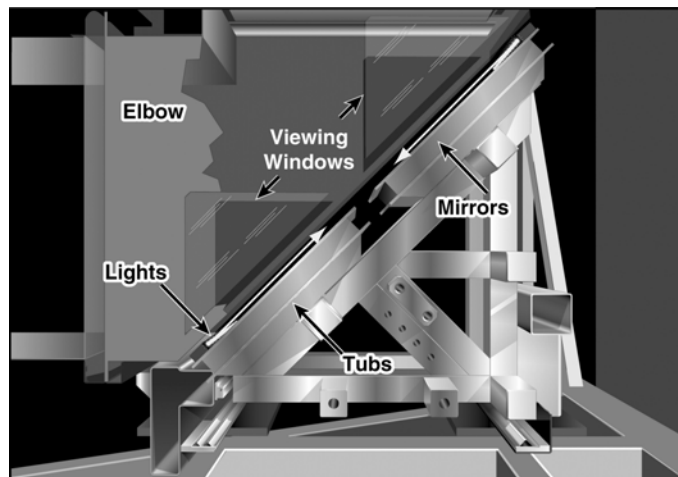


Figure 7: Illustration of an LM5 elbow enclosure, modified with viewing windows, and its mating mirror LRU, modified with grazing-angle illumination provided by bar lights attached to the lower and upper rims of the tubs.

¹ Fiber Optic Systems, Incorporated, 60 Moreland Road Unit A, Simi Valley, CA 93065.



Figure 8: Fiber optic bar light used to illuminate the mirror surfaces.



Figure 9: Photograph of an illuminated LM5 mirror taken through the viewing window in the side of the elbow enclosure.

To remove debris from the mirror surfaces we use a high-speed sheet of gas from a commercial² “gas knife,” a linear nozzle that emits gas from a thin slot (Figure 10). In our application, the gas knives are placed inside the tube between two mirrors and direct the gas sheet laterally across the narrow dimension of the mirrors³ towards their outer edges, as shown in Figure 11. The gas knives are oriented such that each gas sheet is nominally parallel to, and the center of the flow is approximately 0.4 cm above, the surface of the mirror. For an inlet gas pressure of 1.6 MPa (225 psi) and a slot width of 100 μm (0.004”), the measured exit speed of the air exceeds 76 m/s (15,000 ft/min), the limit of our measurement instrument⁴, but falls to 50-60 m/s (10,000-12,000 ft/min) at the most extreme corners of the mirror opposite the gas knife.

² “Super Air Knife” Model 1100027SS (27” Stainless Steel), Exair Corporation, 1250 Century Circle North, Cincinnati, OH 45246

³ Because of physical constraints, blowing “down” the long dimension of the mirror is more difficult to implement and would, in any case, result in lower particle removal efficiency because of the decrease in the gas speed over the longer distance.

⁴ “VelociCalc Plus Meter” model 8385, TSI Incorporated, 500 Cardigan Road, St. Paul, MN 55126.



Figure 10: Photograph of the gas knife.

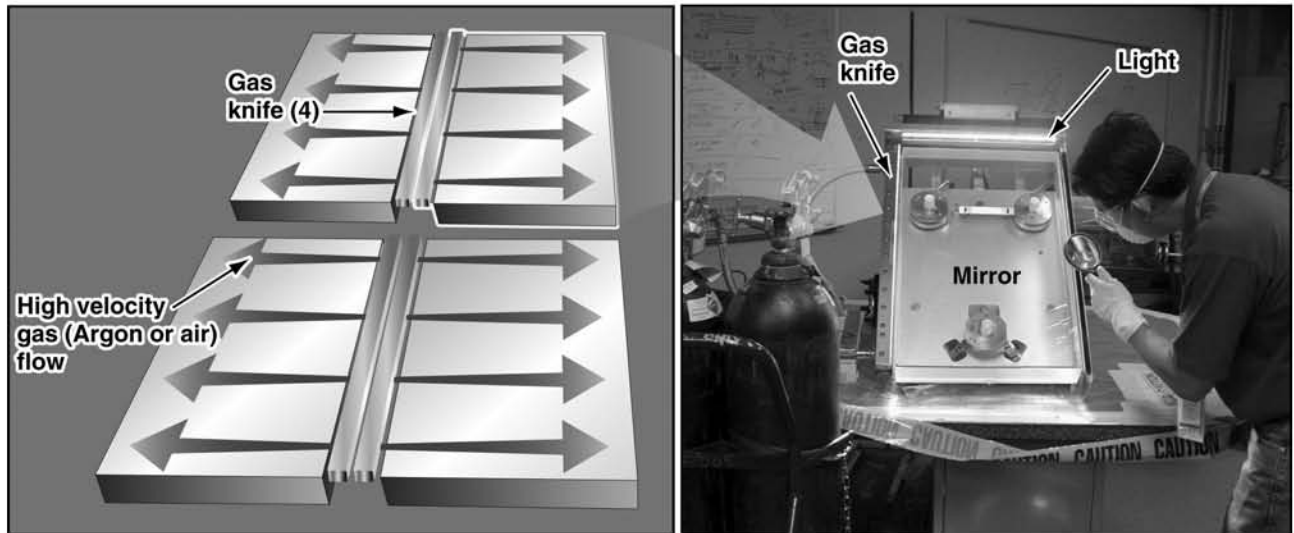


Figure 11: Illustration of the positioning and operation of the gas knives and a photograph of the test apparatus used to perform initial particle removal experiments.

We measured the efficiency of particle removal using the apparatus shown in Figure 12. We mounted an LM5 mirror in a mock tub enclosure and positioned a gas knife at the left edge. A bar light provided grazing angle illumination. We drew twelve squares, approximately 2.54 cm x 2.54 cm (1" x 1"), at representative locations on the mirror and then sprinkled very small samples of test powders of various materials on each area in sequence. We counted the number of particles in each square before (N_0) and after (N) a 1 second pulse from the gas knife and computed the efficiency of particle removal in each location as N/N_0 .

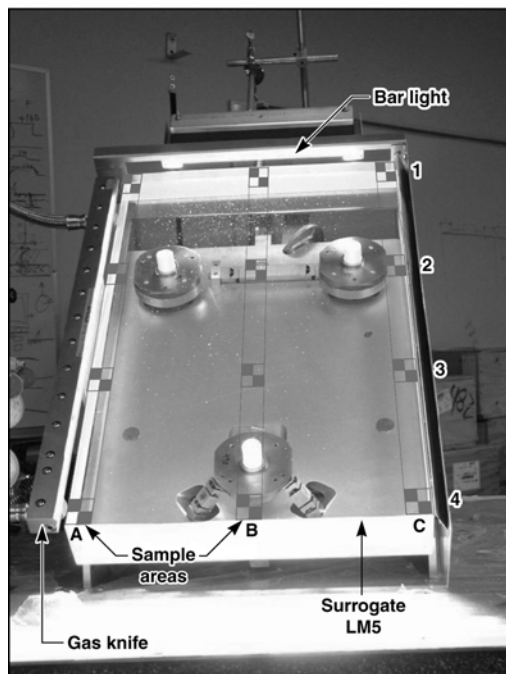


Figure 12. Experimental apparatus used to measure particle removal efficiencies.

We performed our experiments with stainless steel, aluminum, glass and polystyrene particles. The metal powders were prepared by filing bulk metals. This procedure produced irregularly shaped particles, more similar to those we have observed than the spherical metal powders that are commonly available commercially⁵. The glass powder was produced by hand grinding with a mortar and pestle and particles were also irregular in shape. The metal and glass powders were sieved to yield particles within narrow size ranges between 30 μm and 140 μm for the metals and 90 μm and 140 μm for the glass⁶. The polystyrene powder was a commercial product and consisted of very narrowly sized spherical particles with an average size of 48 μm . The polystyrene powder was useful not because it is a convenient surrogate for light organic debris, but because it glows green when illuminated and so is particularly easy to see. For this reason we used it as a “tracer” to allow us to determine where particles re-deposit after they are blown from the mirror surface. Our working performance requirement is that the gas knife be able to remove all test particles 60 μm in size or larger.

3. RESULTS

Results of measurements with stainless steel particles, shown in Figure 13, indicate that the average removal efficiency of the gas knife is >99% for particles >55 μm in size, regardless of the location on the mirror. For smaller particles, the overall average efficiency is less, 96%, and appears to decrease from nearly 100% near the gas knife to about 90% at the far edge. Experiments with nitrogen and argon show that these results are not sensitive to the type of gas used in the gas knife. They are also not sensitive to whether the mirror is in an air or an argon atmosphere when the gas knife is applied. Aluminum particles >55 μm in size are removed with 99.6% overall efficiency, although the efficiency appears to decline to 93-95% at the edge farthest from the gas knife for particles <65 μm in size (Figure 14). Glass particles >90 μm in size are removed with 99.5% efficiency (Figure 15) regardless of location on the mirror.

⁵ Spherical particles also tend to roll off the surface of a tilted mirror.

⁶ We were not able to produce glass particles finer than about 90 μm by hand grinding.

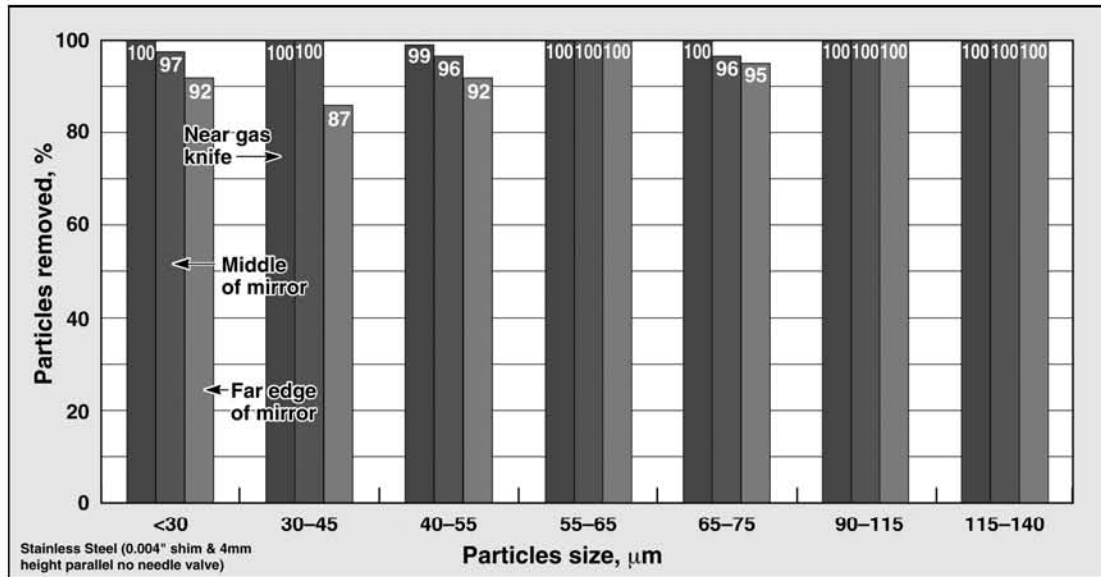


Figure 13: Efficiency of removing stainless steel particles of various sizes from the surface of an LM5 mirror using a gas knife.

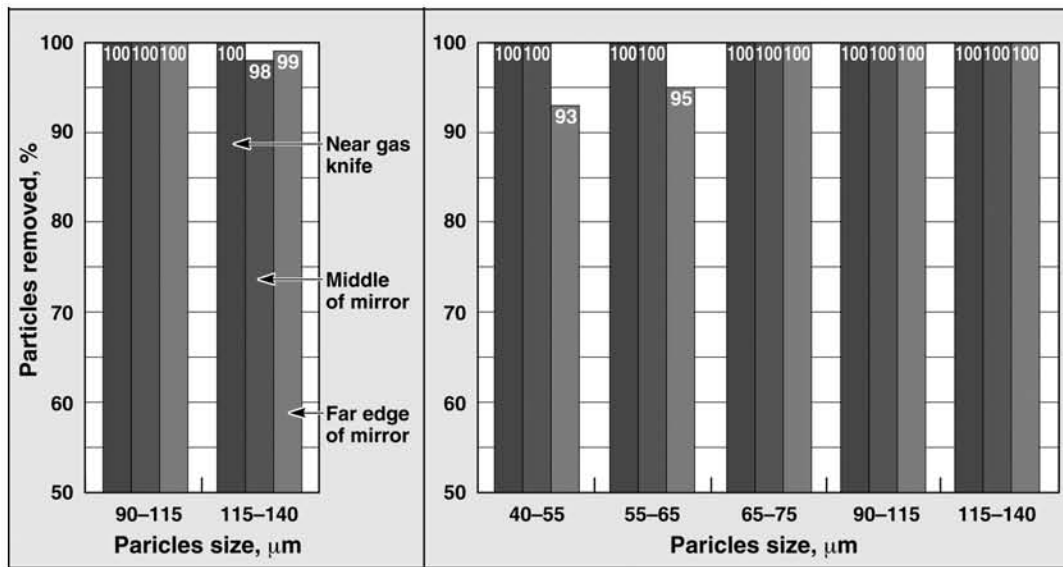


Figure 14: Efficiency of removing glass (left) and aluminum (right) particles of various sizes from the surface of an LM5 mirror using a gas knife.

To confirm the performance of the illumination system, the window design and the gas knife under more realistic conditions than we could achieve with our test apparatus, and to better understand where the particles re-deposit after they are entrained in the gas stream, we installed an elbow and mirror LRU in a clean room, as shown in Figure 15. In this arrangement, the LRU consisted of two LM5 mirrors placed side-by-side in a tub with the gas knives between them as illustrated in Figure 11. Each mirror was illuminated across its full width by a bar light mounted directly to the mirror tub, Figure 16, which had been fitted with a narrow window. Experiments with polystyrene particles showed that 50-60% of these light particles land below both mirrors, 30-35% land on the adjacent mirror and about 10% redeposit on the mirror just cleaned (Figure 17). By applying the gas knife multiple times and alternating between mirrors, we determined that an average of 7-8 gas knife pulses in total are required to remove all of the polystyrene test

particles from the two mirrors. This result is in rough agreement with a simple estimate of 11-12 pulses to achieve 99.9% particle removal based on the observed deposition fractions and the alternate cleaning of each mirror (no multiple pulses on one mirror). Experiments with stainless steel particles⁷ suggest behavior similar to the polystyrene.



Figure 15: Experimental elbow with prototype viewing and debris removal systems in a clean room.

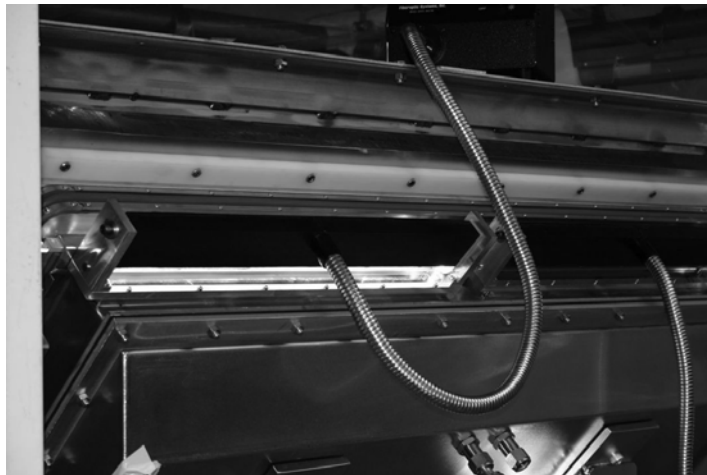


Figure 16: Bar light mounted on the tub of an LM5 LRU mirror tub. Note the window in the tub rim.

⁷ 75-90 μm stainless steel particles were used for these experiments because they were easier to count.

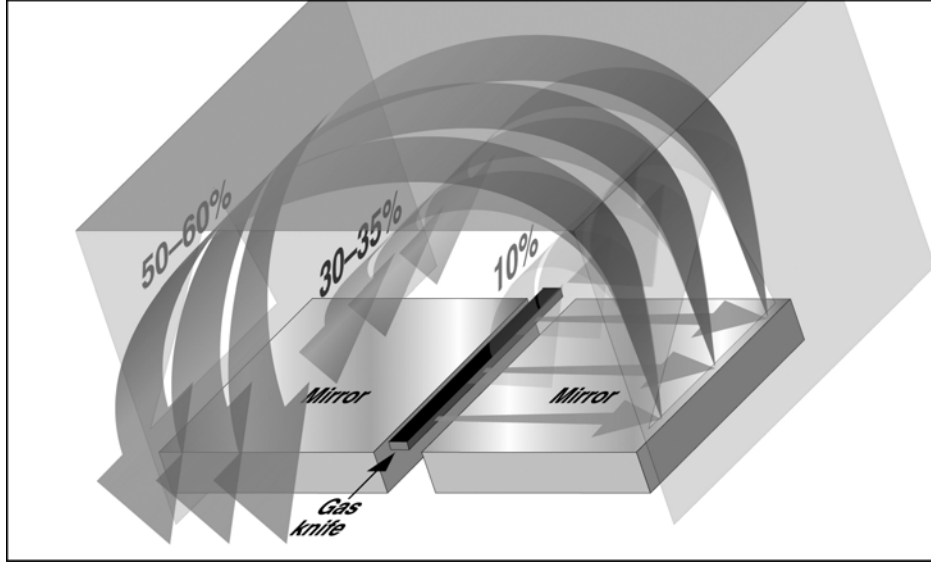


Figure 17: Illustration of particle re-deposition after the gas knife pulse in the experimental elbow.

4. DISCUSSION

Our results demonstrate that the gas knife system we have implemented meets our working requirement for debris removal from the surfaces of LM5 mirrors of the NIF for types of debris typically found in the NIF beam path enclosures. However, experiments in the elbow enclosure show that re-deposition does occur and that multiple pulses from the gas knives will likely be necessary in practice to remove most or all of the surface debris. The particular re-deposition pattern and fractions that we observed, illustrated in Figure 16, is probably caused, at least in part, by the artificial but unavoidable constraint that the experimental elbow has a closure over its top (Figure 15). In the actual installation (Figure 6), the elbow joins to a long, open tube. We therefore expect the actual gas flow and particle re-deposition patterns to be somewhat different than what we have observed⁸. Nevertheless, we suspect that most of the debris will continue to be re-deposited below the mirrors and that alternate pulses will eventually remove all of the debris. Obviously the top mirrors must be cleaned before the bottom ones because most of the debris is re-deposited below the mirrors.

For reasons of laser performance, the atmosphere in which the transport mirrors reside is argon. Nevertheless, we intend to operate the gas knives with clean air, which is readily available near each mirror location. Although this will introduce approximately 0.06 m^3 (2 ft^3) of air per pulse, the total volume of air introduced by the application of multiple gas knife pulses (perhaps as much as 1 m^3 (40 ft^3)) is relatively small compared with the volume of the adjacent beam enclosures. Turbulent mixing produced by the gas knife jet will quickly reduce the concentration of oxygen, as will the flow of argon through the enclosures. Should it prove necessary, however, argon can be used in the gas knives with little or no loss in performance.

An *in-situ* debris viewing and removal system is the most effective of the various options for maintaining the cleanliness of NIF transport mirrors. The alternatives we considered were removal of the LRUs on a regular basis for inspection and cleaning, *in-situ* inspection but removal of LRUs for cleaning (no gas knives), the use of a portable gas supply rather than plumbed air, and the use of argon rather than air in the gas knives. Among these, implementation of the system we have designed appears to offer the least schedule impact at the smallest operating cost. We estimate that

⁸ Note, however, that the flow generated by the gas knives will not be deflected straight up the vertical tube because the mirrors are tilted at 45° . Hence a flow that rises normal to the mirror along the wall of the enclosure will eventually impinge on the wall of the vertical and horizontal tubes opposite to the mirrors.

the operating cost will be very low and the time required to clean the mirrors very short (hours). In many cases it is impossible to access the sides of mirror enclosures, so our assumption in preparing the cost estimates was that the viewing system (light and windows) would be installed on only one elbow in each of the four 48-beam “clusters” of the NIF, but the gas knives, which are part of the mirror assembly, not the elbow, would be installed on *all* upward facing mirrors.

5. CONCLUSION

From this work, we conclude the following:

1. A simple grazing angle illumination system that uses a high intensity fiber-optic bar light provides an effective means of highlighting surface debris as small as 10 μm on the surfaces of the transport mirrors of the NIF.
2. Debris illuminated with the bar light is easily visible to the unaided eye when viewed normal to the illumination direction at a angle of 20-30° through windows placed on the sides of the enclosure.
3. A one second pulse of high-speed (76 m/s) air from a commercially available “gas knife” directed laterally across the mirror close to its surface removes surface debris $\geq 60 \mu\text{m}$ in size with near 100% efficiency.
4. Surface debris between 30 μm and 60 μm in size is removed with efficiencies of 85-96% depending on particle size and the location of the debris on the mirror.
5. The efficiency of debris removal decreases as the air speed decreases with distance from the gas knife.