JTTEE5 5:35-41
©ASM International

Technical Note

A Scientific View of the Productivity of Abrasive Blasting Nozzles*

G.S. Settles and S. Garg

Introduction

ABRASIVE blasting is a sensitive issue in infrastructure refurbishment. Recent environmental laws and resulting costs have brought about a powerful incentive for improvement, but the scientific basis of abrasive blasting has remained essentially the same for over a century. Everyone knows that abrasive blasting "doesn't take a rocket scientist."

However, a rocket propulsion scientist, in fact, can bring about some much needed improvements in abrasive blasting, especially in the efficiency and productivity of blasting nozzles. For instance, the exhaust of the space shuttle main engine contains "shock diamonds," which are characteristic of supersonic flow.

So does a blasting nozzle, although the diamonds are seldom visible to the naked eye. Micrometer-sized alumina particles are accelerated through the nozzles of the shuttle's solid rocket boosters (Ref 1), just as abrasive particles are accelerated through a blasting nozzle. (Actually, it is easier to analyze the shuttle booster problem because the particles are so small.)

This article will explain how some of the extensive knowledge and sophistication of rocket nozzle technology (Ref 2) can be used to improve the productivity of abrasive blasting nozzles. It begins with a brief review of the history and state-of-the-art of blasting nozzles, followed by a somewhat technical explanation of how to improve productivity.

The Evolution of Blasting Nozzles

Abrasive blasting nozzles have a curious evolution. Up to about 1950, simple constant-area or straight-bore nozzles were used (see Fig. 1 from Ref 3). According to Kline et al. (Ref 3), the observation that blasting became more efficient as the nozzle eroded led to the development of modern blasting nozzles with a converging-diverging shape and a minimum throat area.

Of course, this type of nozzle had already been invented by C.G.P. de Laval in 1888 in connection with steam turbines. Apparently, the technology of the Laval nozzle was never actually transferred to abrasive blasting, but rather evolved there on its own. Modern blasting nozzles like those depicted in Fig. 1 are essentially all of the Laval type, though they are mistakenly known as "venturi" nozzles (after a still-earlier invention of G.B. Venturi that refers only to low-speed flows).

Why is the so-called venturi nozzle a better choice for abrasive blasting than the earlier straight-bore nozzle? From the field of gas dynamics (Ref 4) comes an immediate answer: just as in a rocket nozzle, it is the only way to achieve high speed flow at the nozzle exit. The nozzle must contract to a minimum area for the flow to reach the speed of sound, and then it expands to produce supersonic airspeeds. Rocket nozzles like the one shown in Fig. 2 obey the same principle, although in order to be effective at high altitudes, they expand to much larger exit diameters than the earthbound blasting nozzle.

However, blasting nozzles have not benefited from any twentieth-century aerospace technology developments. For example, consider the double-venturi scheme shown in Fig. 1. It is a type of ejector nozzle that entrains outside air, but there is no

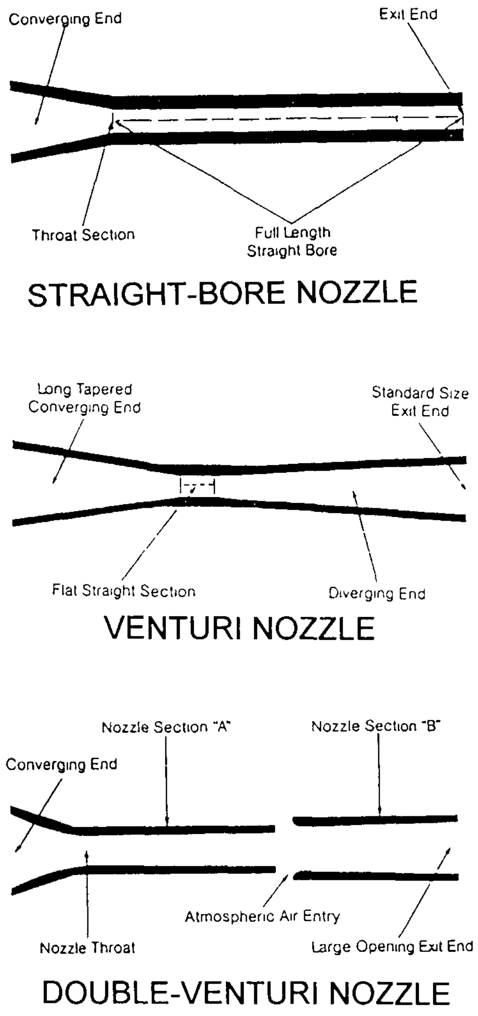

Fig. 1 Blasting nozzles

---

*Reprinted with permission from the Journal of Protective Coatings and Linings, Volume 12, Number 4, April 1995, pp. 28-41, 101 and 102. Note: Some editorial adjustments have been made

G.S. Settles and **S. Garg**, Gas Dynamics Laboratory, Mechanical Engineering Department, Penn State University

scientific basis to expect any higher abrasive particle speed from this. It seems merely to be based on this premise: if 1 venturi is good, 2 should be better. Likewise, the "bazooka" nozzle (Ref 3), which has a higher exit area for a given bore, has no apparent gas dynamic advantage unless operated at a higher pressure. Indeed, the data of Kline et al. (Ref 3) and LeCompte and Mort (Ref 5) reveal that the productivity gains claimed for these nozzles are mostly illusory. A proper scientific study to optimize blasting nozzle design has never been done, and thus represents a considerable opportunity for technology transfer.

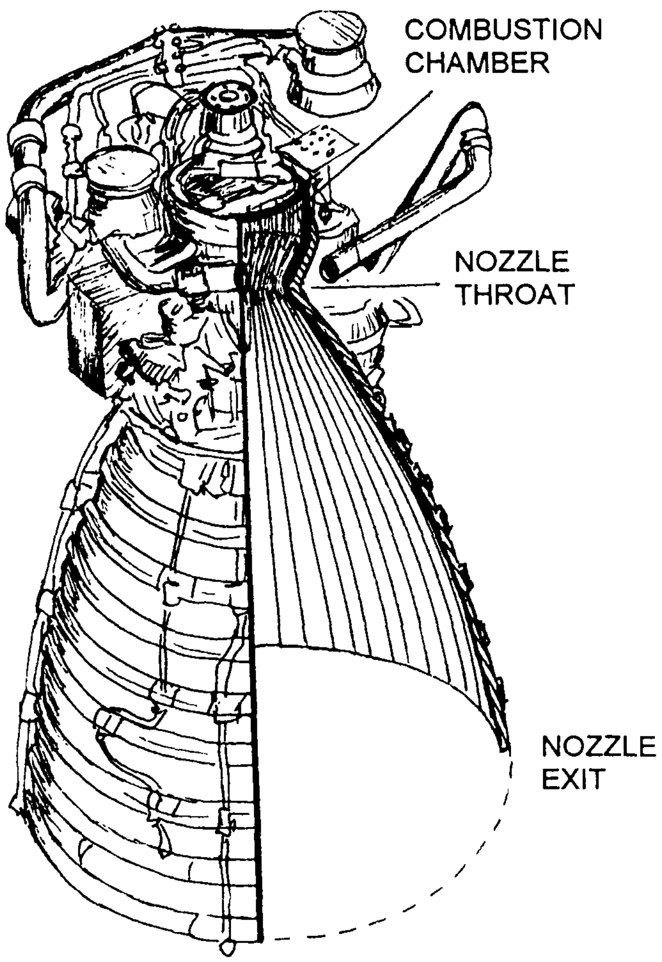

Fig. 2 Cutaway sketch of rocket nozzle.

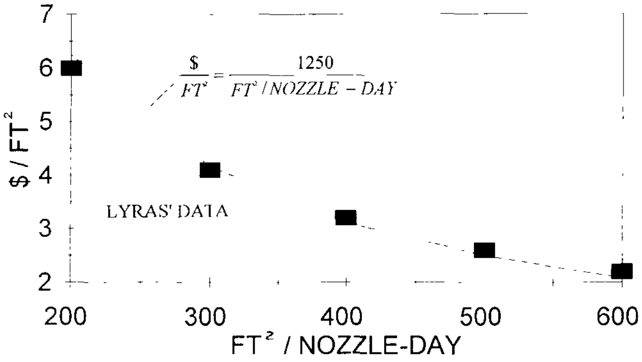

Fig. 3 Abrasive blasting cost/unit area vs. productivity (Lyras, Ref 6)

Goals of Optimizing Blasting Nozzle Productivity

The principal goal of optimizing blasting nozzle design is to improve productivity, usually defined as the number of sq. ft/nozzle-day cleaned by abrasive blasting. (Actually, this definition is inadequate unless the degree of surface cleaning and the thickness and type of coating being removed are also specified.) Why improve productivity? The traditional reason is economy, but, recently, the resulting drop in environmental impact has become equally important.

Lyras (Ref 6) gives an illuminating perspective on productivity. First, he shows that a typical ten-hour shift involves only 4 hours of actual blasting, while the remainder is spent on setup, containment, and work breaks. Abrasive blasting is expensive and labor-intensive, and it is critical that those 4 hours of blasting be done efficiently to minimize paint removal costs.

Secondly, Lyras (Ref 6) shows data revealing an inverse relationship between productivity and cost/sq. ft cleaned. Data from Ref. 6 are reproduced here in Fig. 3, along with a curve fit. Clearly, within Lyras' typical range of productivity, a doubling of productivity cuts the cost per unit area cleaned in half.

What are the economic implications of this? Appleman (Ref 7) finds the "average" bridge paint removal job involves 50,000 to 80,000 sq. ft (4,500 to 7,200 sq. m) of abrasive blast cleaning. Nationwide, some 1,500 bridges are repainted each year. Appleman estimates the total area blast cleaned per year to be between 30 and 72 million sq. ft (2.7 and 6.48 million sq. m). If blasting productivity could be doubled, this estimate along with Fig. 3 shows that the savings could be as much as $100 million per year.

Such an increase in productivity also carries a positive environmental impact. The data of Seavey (Ref 8), replotted here in Fig. 4, show that higher productivity results in less abrasive used per unit area blast cleaned. The scientific reason for this is that at high productivity, each abrasive grain does more work on the surface being cleaned; thus, less abrasive is required in total to do the job. With less abrasive used, less abrasive waste is produced, and the environmental impact is reduced.

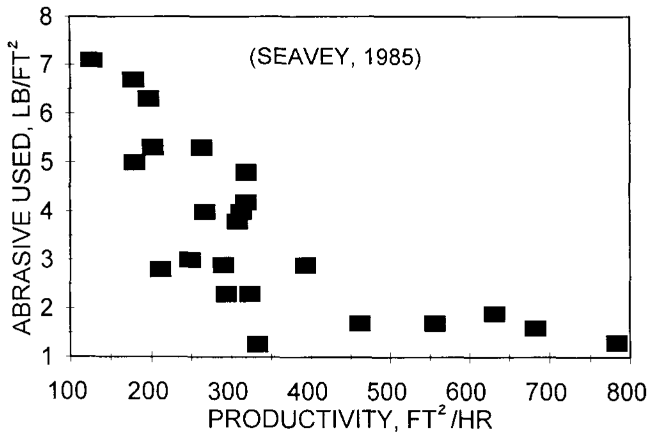

Fig. 4 Abrasive used vs productivity (Seavey, Ref 8).

Increasing Blasting Productivity

Having made a case for higher productivity, let us now consider how it might be accomplished. (In this regards, note that the abrasive effect of a solid particle striking a surface is known to be generally proportional to the kinetic energy of the particle, $1/2\ mV^2$, where V is the particle velocity and m is the particle mass (Ref 9).

From a scientific viewpoint, there are three ways to increase abrasive blasting productivity; (i) run only at the "design" nozzle pressure or above, (ii) run the smallest feasible abrasive grit size, and (iii) use an improved blasting nozzle. Each of these approaches will be considered in turn.

Productivity and nozzle pressure

Seavey's data (Ref 8) are apparently the most detailed results available on blasting productivity as a function of various parameters, including nozzle pressure. When this data are replotted as productivity versus nozzle pressure for various abrasives, Fig. 5 results. It is clear from the figure that productivity rises linearly with nozzle pressure, and that the rate of rise depends upon the abrasive material used.

The fact that there is a rise in productivity with increasing nozzle pressure (Ref 3, 5, 8, 10) is widely recognized in the coatings industry, although the gas dynamics that underlie it have not been explained in any of the literature of the field. Briefly, the drag force on an abrasive particle in an airflow is proportional to the product of its drag coefficient, its size, and the dynamic pressure of the flow, $1/2\rho U$ (Ref 2) where ρ and U are the gas density and velocity, respectively. Increasing the nozzle pressure increases the dynamic pressure in proportion, and this, in turn, proportionally increases the drag force that accelerates the particle through the blasting nozzle.

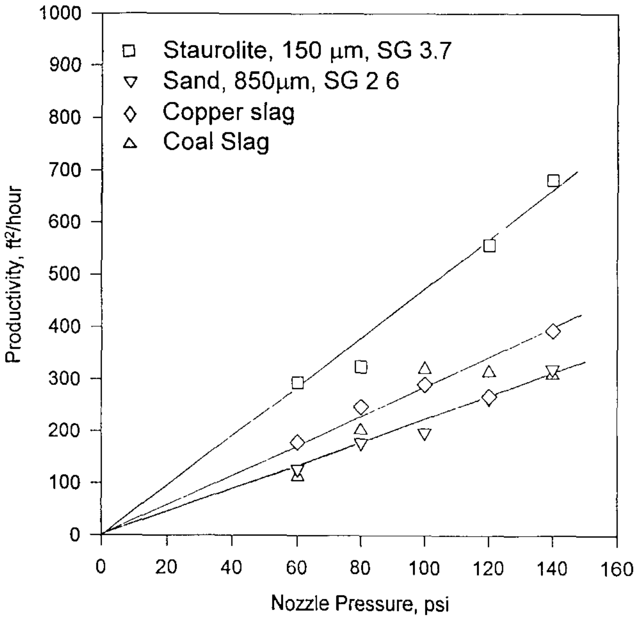

Fig. 5 Productivity vs nozzle pressure (Seavey, Ref 8)

Unfortunately, the dramatic benefits of doubling productivity, described earlier, cannot be had simply by doubling the nozzle pressure. Current blasting equipment is designed to operate around 100 psi (700 kPa) and is not usable at twice that pressure. Worker fatigue due to nozzle thrust ("back pressure") is increased at higher pressures. Moreover, part of the benefit of higher nozzle pressure is lost if the nozzle is not designed to be efficient at such pressures.

So, the more immediate importance of Fig. 5 lies in its demonstration of the productivity loss caused by blasting at low nozzle pressures. Each Laval nozzle has a so-called design nozzle pressure that enables it to produce a supersonic jet of air into the atmosphere with minimum disturbance. When operated below this design pressure, the nozzle forms shock waves that slow both the jet and the abrasive particles it contains. Unlike the case of the space shuttle these "shock diamonds" are not normally visible in abrasive blasting.

However, in Fig. 6, a technique known as Schlieren optics has been used to reveal them in the jet produced by a #7 long-venturi blasting nozzle operated at a pressure of only 60 psi (420

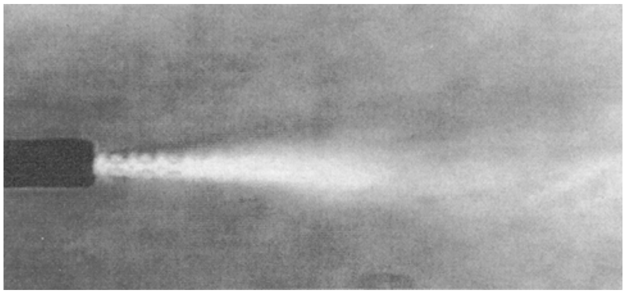

Fig. 6 Schlieren image of jet blasting nozzle below design pressure

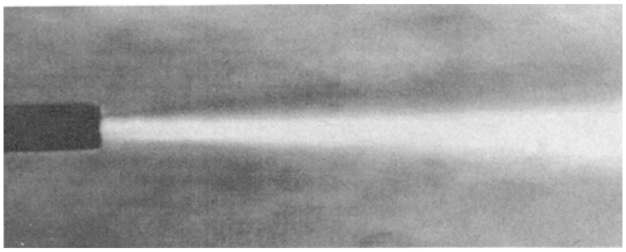

Fig. 7 Schlieren image of jet blasting nozzle at design pressure.

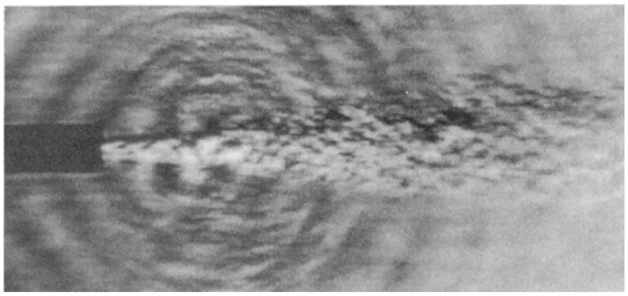

Fig. 8 Same as Fig. 6, but microsecond exposure reveals sound radiation.

kPa). By contrast, the same nozzle at its design pressure of 115 psi (800 kPa) produces a smooth supersonic jet at about Mach 2 with no shock waves (Fig. 7). Finally, Fig. 8 repeats the low-pressure case of Fig. 6 with microsecond illumination to capture the ripple-like sound waves radiated by the jet. It is well known in aerospace nozzle technology (Ref 11) that a phenomenon known as "screech" produces very high sound levels when Laval nozzles are operated well below design pressure.

The upshot is that abrasive blasting with low nozzle pressure yields poor productivity and high noise levels. It is thus wise to run at least at the design pressure for the nozzle being used, and higher if possible. One can find the design nozzle pressure, which depends on bore/exit area ratio, from the graph shown in Fig. 9 (based on theory found, for example, in Ref. 4). For proper operation, it is important to monitor the pressure just before the nozzle, not the pressure entering the blasting hose.

Increasing Productivity Through Abrasive Grit Size

Since solid particles in an airstream are much denser than the air, their inertia generally prevents them from accelerating as rapidly as does the air itself. Compared to many airborne particles, abrasive blasting grit is particularly large and heavy, so the inertia problem is a serious one. Its effect is obvious in Fig. 5, where staurolite grit of 150-micrometer mean size accelerates much more readily than 850-micrometer sand, thus yielding higher productivity (despite the fact that staurolite is denser than sand).

$$\text{AREA RATIO} = \left(\frac{\text{EXIT DIAMETER}}{\text{BORE DIAMETER}}\right)^2$$

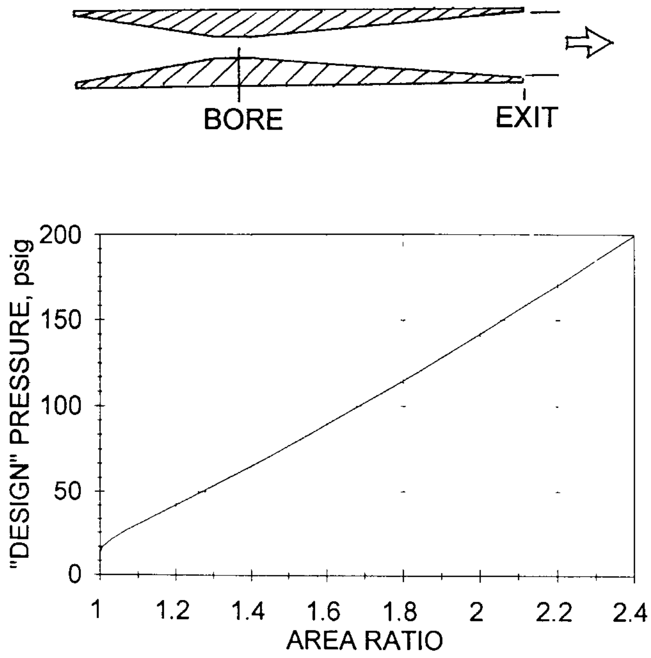

Fig. 9 How to find the design pressure of a blasting nozzle

For further exploration of this issue, a computer model was written for airflow through a Laval nozzle and its acceleration of small solid particles. The air and particle properties and the nozzle geometry are inputs to this computer program, which predicts both the gas flow (see Ref. 4 for more information) and the particle motion through the nozzle. For simplicity, only a single spherical abrasive particle is considered; thus, no account is taken of particle loading or multiple-particle collisions in this computer model. The program tracks the abrasive particle through the nozzle, calculating the drag force on it at each step along the way. The result is a calculated particle speed V at the nozzle exit, which is generally not the same as the gas speed U at that point.

Experimental verification of the computer model was carried out using an existing Laval nozzle operated at its design pressure and particles of aluminum and stainless steel, both in the range of 50- to 70-micrometer mean diameter. Particle exit velocities from the nozzle were measured by "streak photography," (Ref 12) using a high-speed video camera with an accurate, known shutter speed.

The result, shown in Fig. 10, portrays the computed results as lines and the experimental data as symbols in a plot of velocity versus distance along the nozzle axis. While the airflow reaches 500 m/s (1,650 ft/s) at the nozzle exit, the particles lag behind and achieve only about 200 m/s (660 ft/s) exit speed. The agreement is excellent for the aluminum particles and good for the steel particles, giving us confidence that the computer model yields a reasonable prediction of the physical problem at hand.

Next, a computer model prediction of the effect of a particle's size on its velocity through a representative blasting nozzle 0.2 m (8 in.) long was made. The nozzle was designed for Mach 2 exit flow (twice the speed of sound) and was operated at the corresponding design pressure of 100 psi (700 kPa). Particles with specific gravity of 1.0 and diameters of 10, 100 and 1,000 micrometers were computed. Results are shown in Fig. 11. Ten-mi-

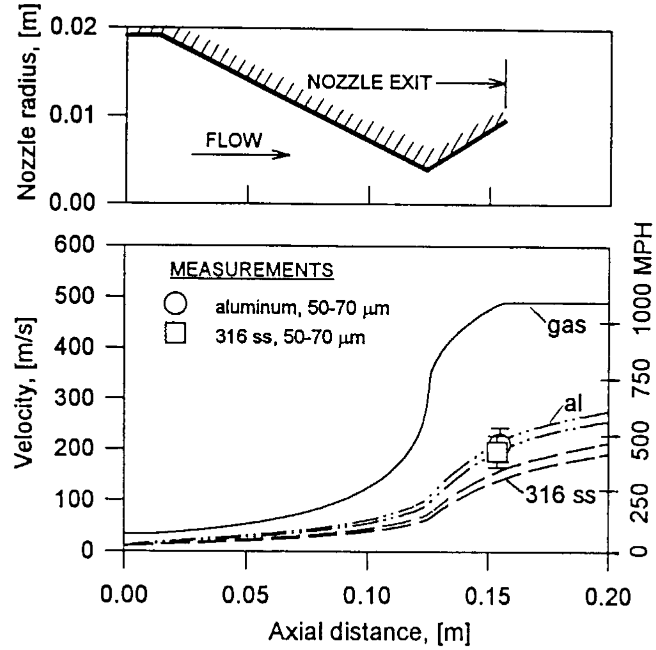

Fig. 10 Predicted and measured velocities through a Laval nozzle

crometer particles lag behind the airflow somewhat but manage to achieve more than 80 percent of the air velocity at the nozzle exit. The 100-micrometer particles lag more seriously and reach only about half the air velocity at the nozzle exit. The 1,000-micrometer (one-millimeter) diameter particles are barely accelerated at all by the airflow in the nozzle.

The upshot of this example calculation is clear. Large, heavy abrasive particles will be poorly accelerated by a blasting nozzle and will result in poor productivity. It is strongly recommended that, consistent with the minimum anchor pattern and other blasting constraints, one should use the smallest feasible abrasive grit size to achieve high productivity.

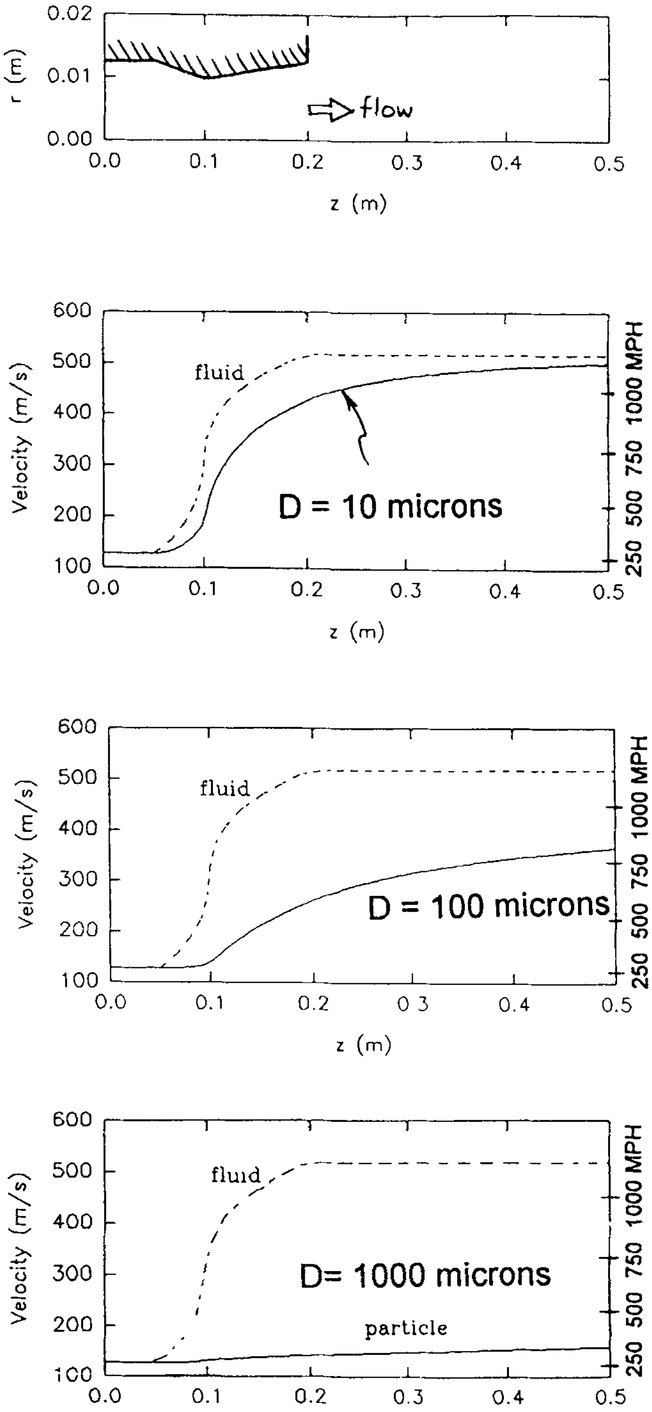

Fig. 11 Computed velocities of various sized particles through a blasting nozzle.

Nozzle Design and Blasting Efficiency

Finally, in addition to the nozzle pressure and grit size effects described above, nozzle design has an effect upon blasting productivity. The exact contour of the nozzle, its length, and its bore/exit area ratio all affect the maximum acceleration of particles that it is able to achieve. The computer model, described and verified above, allows us to examine the relative effects of these nozzle design parameters.

A computation has been made using the contour of a standard #7 long-venturi blasting nozzle. For a direct comparison with the detailed data of Seavey (Ref 8), staurolite grit of 150-micrometer mean size and 850-micrometer sand have been modeled. (The specific gravities of these materials are 2.6 and 3.7, respectively.) The results of the computation are shown in Fig. 12 as a plot of velocity versus distance along the nozzle axis. A scaled sketch of the nozzle cross section is provided below the horizontal axis for reference.

The exit speed of the airflow in Fig. 12 is about Mach 2.13 (533 m/s or almost 1,200 mph). As expected, the particles lag behind. The sand particles reach a predicted exit speed of only 173 m/s (570 ft/s), while the heavier but much smaller staurolite grit exceeds 200 m/s (660 ft/s). The staurolite's momentum advantage over the sand translates directly into higher blasting productivity, as shown in Fig. 6. Unfortunately, Seavey made no particle velocity measurements that might have been compared directly with the predictions shown in Fig. 12.

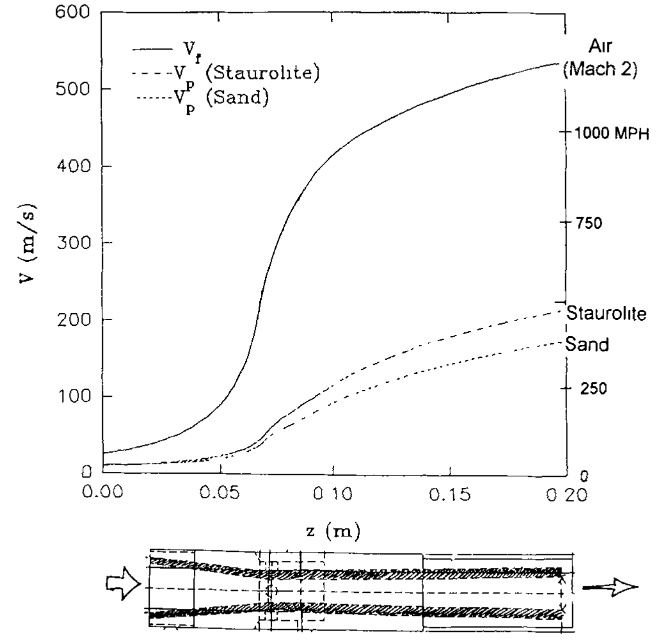

Fig. 12 Computed velocities of Seavey's abrasive particles through a #7 long-venturi blasting nozzle (Seavey, Ref 8).

Typical abrasive blasting nozzle efficiency can be approximated by comparing the kinetic energy flux of the airflow and particle streams at the nozzle exit. For this purpose, we adopt the conditions of the blasting tests performed by Seavey (Ref 8), which resulted in the most complete data set currently available. Seavey used a standard 9.5-millimeter-bore long-venturi blasting nozzle operated at 700 kPa (100 psi) to blast sand of 850-micrometer mean diameter at a rate of 580 kg/hr (1,280 lb/hr), and at a particle load factor of unity. The mass flow rate of the gas is computed as if particles were not present, and is found to be 0.16 kg/s (0.35 lb/s). The nozzle exit speed of the gas is U = 533 m/s (1,760 ft/s) as noted above. Thus, the kinetic energy flux or power of the airstream alone, given by the expression {1/2 × (mass flow rate) × U (Ref 2)}, is 23.3 kW. (This is a reasonable estimate, considering that the air compressor required for such a blasting operation is specified as 33 kW or 44 hp by Hansel). (Ref 13)

In contrast, the abrasive sand stream in Seavey's tests has the same mass flux as the airstream but a nozzle exit velocity, from the computation shown in Fig. 12, of only 173 m/s (570 ft/s). In this case, the power of the sand particles is only 2.4 kW, or about 10 percent of the power of the airstream. Thus, using Seavey's sandblasting experiment as a typical example, the overall efficiency of the blasting process is about 10 percent when sand is the abrasive. Staurolite abrasive, being smaller and easier to accelerate, yields a better efficiency, as discussed earlier.

Ten percent is not a good efficiency level. In other words, 90 percent of the energy of the compressed air stream is not being transformed into any useful work on the surface being cleaned. This result is a strong indication that dramatic improvements are possible. For example, the efficiency of the process (and thus the productivity) could presumably be doubled and still be only in the 20 percent range.

What efficiency level is possible in abrasive blasting? Clearly, 100 percent is not possible, since that would involve a total energy transfer from gas to particles with no residual gas energy. As a rough guide, an efficiency analysis by Gregor (Ref 14), assuming variable particle size and density, load factor, and nozzle geometry, found the possible efficiency levels to vary between 3 percent and almost 60 percent. It seems, then, that a doubling of typical abrasive blasting efficiency is not out of the question.

In a further exploration of nozzle efficiency, a preliminary examination was made of various modifications in nozzle size and contour, beginning with the standard long-venturi nozzle shown in Fig. 12. For example, Fig. 12 reveals little or no particle acceleration up to the nozzle bore (throat), so that the initial portion of the nozzle is not contributing at all to blasting productivity. By a combination of nozzle design changes based on technology transfer from rocket propulsion, we obtained an estimated exit velocity of 230 m/s (760 ft/s) for Seavey's 850-micrometer sand particles.

Since the kinetic energy of the sand stream goes as V (Ref 2), this improvement raises the calculated efficiency of the overall blasting process from 10 percent to 18 percent, which approaches a doubling of efficiency. Such a prediction requires extensive experimental verification, but nonetheless indicates the potential for dramatic improvement in abrasive blasting nozzle efficiency.

Finally, note that the development of a more efficient blasting nozzle would increase productivity, thus getting the job done more quickly and more cheaply and creating less waste abrasive, as described earlier. Moreover, this would require only the quick and relatively inexpensive replacement of the nozzle, with no other modification of existing blasting equipment.

Summary: A Considerable Opportunity

In summary, abrasive blasting has a lot to gain by technology transfer from aerospace disciplines such as gas dynamics and rocket propulsion. These disciplines lend a scientific basis to abrasive blasting. They help explain why blasting nozzles behave the way they do and how their performance can be improved.

In this regard, some guidelines are already clear. For example, for maximum productivity, nozzles should always be operated at or above their design pressure, and one should always choose the smallest usable grit size consistent with the requirements of the blasting job.

However, the best opportunity for a dramatic increase in blasting productivity appears to lie in improved nozzle design. Abrasive blasting nozzles have never been optimized by any modern scientific methods. An example computation shows a typical blasting operation to be only about 10 percent efficient. Preliminary research has indicated that this figure can be raised to 18 percent purely by improved nozzle design. We believe further improvements are possible by optimizing nozzle design, pressure, grit size, and load factor.

The economic incentive to carry out such an optimization is considerable. Given the surface area of highway bridge steel blast cleaned each year, current overall blasting cost levels, and an inverse relationship between cost and productivity, a doubling of blasting productivity could save as much as $100 million yearly in US bridge reconditioning costs. This appears possible by following the guidelines developed here and replacing current blasting nozzles with an improved version still to be developed, without modifying the remainder of the blasting rig. A positive environmental impact due to reduced waste abrasive would also accrue.

The field of abrasive blasting is wide open for technology transfer, but requires a proper, funded research program to carry out the necessary modeling, laboratory experiments, and field testing of new nozzles to realize the improvements described above. Thus, a considerable opportunity exists for a modest research and development investment in blasting nozzle design to pay off in large scale for the protective coatings community and for the civil infrastructure.

Acknowledgment

The assistance of the Marthens Co. in providing blasting equipment and of Dr. D.W. Kuntz in providing a computational subroutine is gratefully acknowledged.

References

1 D.J Carlson and R.F. Hoglund, "Particle Drag and Heat Transfer in Rocket Nozzles," AIAA Journal, Vol. 2, No 11, November 1964, pp. 1980-1984

2 G P. Sutton, Rocket Propulsion Elements, 6th edition, John Wiley & Sons, New York, NY 1992.

3. E. Kline, G. Mort, and J. LaCompte, "Improved Productivity from New Blast Nozzle Geometry," Journal of Protective Coatings & Linings, February 1988, pp. 8-12.

4 J E A. John, Gas Dynamics, 2nd edition, Allyn and Bacon, 1984

5. J. LeCompte and G Mort, "The Importance of Proper Blasting Nozzle Selection and Use," Journal of Protective Coatings & Linings, November 1986, pp. 3-6.

6. L.G Lyras, "The Cost of Lead Paint Removal," Journal of Protective Coatings & Linings, July 1991, pp. 56-63.

7 B R. Appleman, "Bridge Paint: Removal, Containment, and Disposal," NCHRP Synthesis 176, Transportation Research Board, NRC, February 1992.

8. M. Seavey, "Abrasive Blasting Above 100 psi," Journal of Protective Coatings & Linings, July 1985, pp. 26-37

9. I Finnie, J Wolak, and Y. Kabil, "Erosion of Metals by Solid Particles," Journal of Materials, Vol. 2, No. 3, September 1967, pp 682-700.

10. J Rex, "A Review of Recent Developments in Surface Preparation Methods," Journal of Protective Coatings & Linings, October 1990, pp 50-58

11. S.P Pao and J M Seiner, "Shock-Associated Noise in Supersonic Jets," AIAA Journal, Vol. 21, May 1983, pp. 687-693

12 E F C. Somerscales, "Tracer Methods," in Methods of Experimental Physics—Fluid Dynamics, Vol.18, Part A, ed. R J Emrich, Academic Press, New York, NY, 1981.

13. D. Hansel, "Abrasive Blast Cleaning—Vital Foundation for Coating Cost and Success," Materials Performance, August 1986, pp 15-20.

14 W Gregor, "Dispersed Two-Phase Flows at High Velocities," Encyclopedia of Fluid Mechanics, ed. N.P Cheremisinoff, Vol. 4, Ch 13, 1985, pp 399-420