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Evaluation of Productivity, Consumption, and Uncontrolled Total Particulate Matter Emission Factors of Recyclable Abrasives

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EVALUATION OF PRODUCTIVITY, CONSUMPTION, AND UNCONTROLLED TOTAL PARTICULATE MATTER EMISSION FACTORS OF RECYCLABLE ABRASIVES

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Abstract

Dry abrasive blasting is a commonly used surface preparation operation by many process industries to clean up metallic surfaces and achieve surface finishes suitable for future adhesion. Abrasives used in this process can be recyclable or expendable. This study was undertaken to evaluate the performance of three recyclable abrasives: garnet, barshot and steel grit/shot in terms of productivity (area cleaned per unit time), consumption (amount of abrasive used per unit area cleaned) and uncontrolled total particulate matter (TPM) emission factors (in terms of mass of pollutant emitted per unit area cleaned and mass of pollutant emitted per unit mass of abrasive consumed). Though there have been various attempts in the past to evaluate the performance of these abrasives, there has not been a streamlined approach to evaluate these parameters in the commonly used range of process conditions, or to identify and model the influences of key process variables on these performance parameters. The first step in this study was to evaluate the performance of these three abrasives in blasting painted steel panels under enclosed blasting conditions and using USEPA recommended protocols. The second step was to model the influences of blast pressure and abrasive feed rate, two most critical parameters on productivity, consumption and emission factors. Two and three dimensional models were obtained using multiple linear regression techniques to express productivity, consumption and TPM emission factors in terms of blast pressure and abrasive feed rate.

Barshot was found to have high productivities over all and steel grit/shot demonstrated the least emission potential at almost all of the tested pressure and feed rate conditions. The data will help fill the gaps in literature currently available for dry abrasive blasting performance. The models obtained will help industries, the research community and the regulatory agencies to

make accurate estimates of the performance parameters. Estimating productivity and consumption will help industries identify best management practices by optimizing the process conditions to achieve high productivity and low consumption rates. Emission factor determination will help in reducing the emissions to the atmosphere by choosing process conditions corresponding to minimum emissions. The performance parameters once optimized can result in reduction in material, labor, energy, emission and disposal costs, lower resource utilization and hence reduction in overall life cycle costs of dry abrasive process. The developed models will help industries in making environmentally preferable purchases thereby promoting source reduction options. PM emissions estimated using the models presented here will aid studies on health risk associated with inhalation of atmospheric PM.

1.0 Introduction

Surface preparation is defined as the process of removing contaminants such as oil, dust, paint, soil, or grease before coating, lining or ink applications [1]. It also provides a measure of future corrosion prevention from a coating system. Many surface preparation operations are commonly used and the choice of the operation depends on the substrate, coating, process efficiency and the final surface finish obtained. Abrasive blasting is a well known surface preparation operation widely used by many industries. If properly done, abrasive blasting can be used to thoroughly clean a surface and create a profile suitable for adhesion. It is recognized as the most effective means of obtaining the desired surface cleanliness and profile [2]. Abrasive blasting can either be air assisted or water assisted. Abrasive blasting uses the mechanical energy of abrasive accelerated at high speeds against surfaces to remove paint and other organic coatings. The common methods of blasting use either air or water pressure. These methods use the force of compressed water or air respectively to expel the abrasives at the substrate [3].
The scope of this dissertation is restricted to air assisted blasting also known as *dry abrasive blasting*.

In air assisted blasting or dry abrasive blasting, a stream of abrasive particles is forcibly propelled at very high velocities to impact and thereby clean the target metal substrate [2]. The high velocity abrasive particles create clean surfaces with even roughness thus preparing them for new coatings. Dry abrasive blasting also helps to eliminate the use of organic solvent stripping and hence the generation of toxic waste material. Dry abrasive blasting has the following applications in process industries:

1. Removal of rust, scale, and paint,

2. Roughening metal surfaces in preparation for coating, painting or other types of bonding,
3. Removal of burr,
4. Development of a matte surface finish,
5. Flash removal from molding operations [4].

Industries using abrasive blasting for surface cleaning and texturing include:

1. Maritime industry (shipbuilding and repair)
2. Chemicals manufacturing plants
3. Automobile manufacturing
4. Air craft manufacturing
5. Oil exploration, storage, and refining
6. Municipal corporations (water treatment units, wastewater treatment units, and bridges)
7. Dental material manufacture
8. Construction and
9. Foundries.

Abrasive materials are classified by the United State Environmental Protection Agency (USEPA) as follows: (a) sand, (b) slag, (c) metallic shot or grit, (d) synthetic and other [5]. Abrasives can also be broadly classified as recyclable (re-useable) and non recyclable (expendable). Sand and slag abrasives are non recyclable whereas metallic abrasives (specular hematite, steel shot and grit, etc), and garnet are recyclable. Steel grit and other metallic abrasives can be reused a multiple number of times owing to their high reuse factor. Abrasive selection is dictated by the scope of the job, location of the job, initial surface contamination, final desired surface finish, abrasive properties and cost [2]. If an abrasive can be reused a multiple number of times without compromising on process productivity, it will result in reduction of material costs, waste disposal costs and hence the overall life cycle costs of dry abrasive blasting process.

Dry abrasive blasting has significant environmental impacts owing to the nature of the process, properties of materials used and the physiochemical transformations they undergo during blasting. Abrasive particles undergo physical breakdown and these particles along with the surface contaminants (rust, paint, coating, etc), and other material get airborne and constitute the total particulate emissions from the process. The solid wastes generated during the process include the used or spent abrasives and the surface contaminants that settle down on the ground. Abrasive blasting has been associated with various occupational diseases owing to the contaminants released while blasting and noise induced hearing loss from excessive noise exposure associated with the blasting process. Sand has been used for blasting conventionally and hence the process is also referred to as sand blasting. Sand blasting causes respirable free silica to get airborne. The result of long-term exposure to free silica in the lungs causes *silicosis* (a respiratory disease caused by inhalation of fine respirable quartz or free silica contained in the dust).

In 1997, the International Agency for Research on Cancer has classified inhaled crystalline silica from occupational sources as carcinogenic to humans, and categorized it as an IARC Group 1 agent. Mine Safety and Health Administration (MSHA, US Department of Labor) has reported that due to dry abrasive blasting, there is an increase in concentrations of CO_2, NH_3, SO_2, CO and particulates and a decrease in respirable oxygen in the working atmosphere. Particulates emitted from blasting are in various size fractions (PM_1, $PM_{2.5}$, PM_4, and PM_{10}). Blasting of lead painted structures causes health concerns about lead exposure. Health hazards to personnel involved in blasting include physical injury from the abrasive projectile stream, respiratory hazards from abrasives used or target surface components, and noise from air supply inside the personal protective helmet used by the blaster, and outside from the blasting activities. Blast pot operators and other site workers are generally also exposed to some dust and significant noise levels of which the latter are most likely to be excessive. Blasters are also faced with the danger of excessive levels of radiation exposure while using abrasives (heavy mineral sands) containing excessive levels of radioactive material (thorium from monazite contamination). Use of slag and metallic abrasives lead to release of particulates and particulate metals in addition to pollutant gases and copollutants. Based on the abrasives, the emissions can include iron, chromium (total and hexavalent), lead (from painted surface blasting), and other carcinogenic and non carcinogenic metals. The pollutants released from blasting sources get transported (by atmospheric dispersion) to ambient air thereby depleting the ambient and indoor air quality.

The dry abrasive blasting process category is regulated by the following federal and state regulations for solid, hazardous waste generation and the atmospheric emissions of gaseous and particulate pollutants. In 1990, the Clean Air Act was adopted as a federal law for the entire country under which the USEPA sets limits on pollutant limits in the air in the USA. The law ensures that all Americans have the same basic health and environmental protections. The states are responsible for implementing the act by developing state implementation plans (SIPs) explaining how the implementation will be carried out [6]. To protect public health, the USEPA also established National Ambient Air Quality Standards (NAAQS) for six pollutants categorized as *criteria pollutants* (CO, Pb, NO_2, O_3, Particulate Matter and SO_2). Since the size of particulates has a major role in its adverse health effects, the USEPA categorized PM sizes into *ultrafine* (less than 0.1 μm), *fine* (less than 2.5 μm) and *coarse* (2.5 - 10 μm) based on the aerodynamic diameter of the particles [7]. Standards of performance for new stationary sources (New Source Performance Standards, NSPS) have been given in detail in the 40 CFR 60, Chapter I, Subchapter C which regulates the emissions from any potential new source [8]. The Occupational Safety and Health Administration (OSHA) proposes and periodically modifies Permissible Emission Limits (PEL's) on pollutants emitted and their size fractions after carefully considering the short term and long term health effects of airborne pollutants. The solid waste (spent abrasive, surface contaminants and other material) generated during blasting has to be disposed to secure landfill sites. Once the spent abrasive is found to be unfit for reuse, it is subjected to the Toxicity Characteristic Leaching Procedure (TCLP) to estimate metal compositions [9]. TCLP helps in categorizing the used abrasive to determine if it is a hazardous waste or an industrial solid waste based on contaminant levels. Used abrasive categorized as hazardous is disposed of in hazardous waste landfills and others are disposed of in industrial solid waste landfills.

The *performance* of dry abrasive blasting process is measured using the following output parameters:

1. *Productivity*: measure of speed of cleaning by an abrasive defined as area cleaned (sq ft or m^2) per unit time(hour)
2. *Consumption:* measure of the amount of abrasive used (kg) for blasting a given area (m^2). This is a direct measure of the solid waste generation potential of the abrasives. As mentioned earlier, based on the toxicity characteristics of the wastes generated (spent abrasives, surface contaminants, and other materials), abrasive consumption rate relates to amount of hazardous wastes generated by blasting process.

3. Atmospheric emissions: from the process is a measure of the emissions from the process in the form of particulate matter (PM) as well as gaseous pollutants.

The performance of an abrasive is influenced by the following characteristics:

1. Initial surface contamination
2. Desired final surface finish
3. Abrasive breakdown rate (measure of abrasive's cleanliness)
4. Size of abrasive particles
5. Particle geometry (shape)
6. Abrasive embedment
7. Hardness, and
8. Recyclability / reusability.

Productivity, consumption and emissions from the process have a direct and strong impact on process efficiency; overall process life cycle costs; landfill area requirements and costs; as well as associated human health effects and environmental impact. Available literature for productivity, consumption and emissions for blasting is discontinuous and insufficient both to evaluate the performances of individual abrasives and to obtain a clear cut understanding of the influencing process parameters. Identifying the dependency of productivity and consumption on process parameters is essential to reduce wastes and associated costs. Thus, there is need to evaluate these performance parameters for the individual abrasives and model the influences of influencing factors on them using standardized test procedures and uniform test conditions.

This dissertation was undertaken to evaluate the productivity, consumption and emissions of a group of three recyclable abrasives: *garnet, specular hematite (bar shot) and steel grit/shot* used for blasting painted metal substrates. Further, mathematical (regression) models relating productivity, consumption and emissions to the most critical process parameters were obtained for these three abrasives for blasting of painted steel panels as part of the research. The details of the literature reviewed, research objectives, experimental methodology used, results and conclusions are presented in the subsequent chapters.

2.0 Literature Review

This chapter presents the review of available literature on dry abrasive blasting, the important factors affecting productivity, consumption and emissions, the health effects of the waste streams generated during blasting, current data available for blasting and life cycle cost components of blasting.

2.1 Process Description

Dry abrasive blasting is a pressure assisted process in which abrasive particles are propelled using compressed air onto the target metal surface to remove the surface contaminants and achieve a finish and profile further painting, coating or similar applications. Based on literature collected from various sources namely industry white papers federal and state organizational documents, three basic components have been identified in blasting operations: equipment, abrasives and personnel. It is important to choose these three with due care to ensure the desired process output.

2.1.1 Blasting equipment

The compressed air source, blasting machine or blast pot and the nozzles used for blasting are the three most important components used in any kind of blasting.

Air Compressor:

The air compressor is the costliest and most difficult to maintain component of blast cleaning systems. The volume and pressure of compressed air directly affect the velocity of abrasives at the nozzle thereby determining blast productivity, material consumption rates and air emissions. Hence, maintaining the nozzle pressure and air volume is critical for blasting operations. The nozzle pressure is determined by the nozzle diameter and the compressed air pressure. For example, using a 3/8th inch nozzle, to get a nozzle pressure of 100 PSI, a 44 hp compressor providing an air flow of 196 cfm is required. Compressor sizes are dictated by nozzle orifice size, nozzle pressure, and head losses due to hoses and couplings, and secondary air supply to blaster. Gasoline and diesel compressors are the best for use for outdoor blasting operations.

Blast Pot:

The blasting machine commonly known as *blast pot* should be designed to meet safety regulations and must be ASME-coded. The design and capacity influence their efficiency and productivity. Air pressure inside the pot must be equal to that of the air flowing through the external piping. The important components of the blast pot include:

1. An automatic pop up valve that closes when the compressor is turned on and opens when the pressure is released,
2. A concave head section for loading the abrasive into the pot, and
3. A conical hopper at the bottom for continuous flow of abrasive into the feed valve.

Figure 1 shows the schematic of a blast pot and the various components.

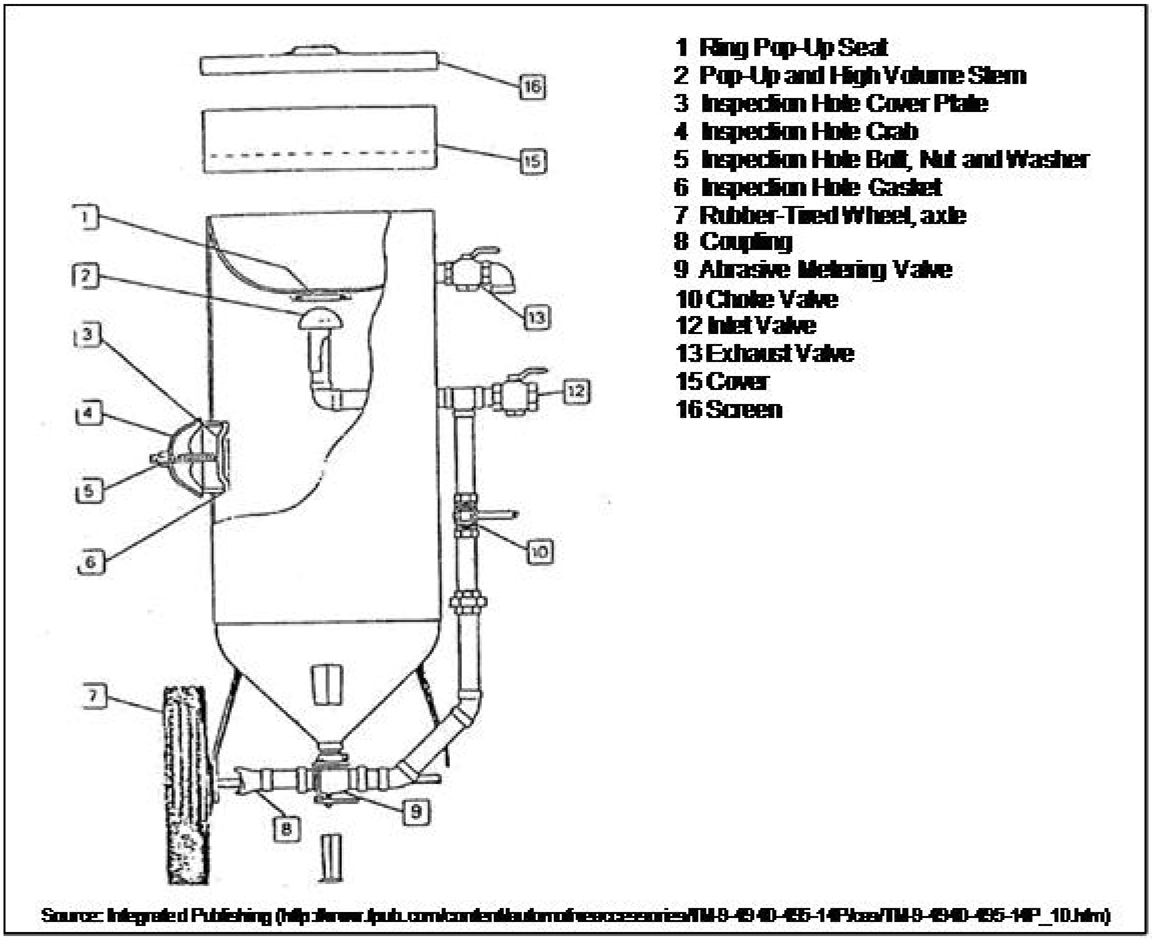


Figure 1 Schematic of a Blast pot

Abrasive Metering Valve:

Abrasive metering valves are feed valves fitted at the bottom region of the blast pot to regulate the fine flow of abrasives and thereby the abrasive feed rate. It regulates the abrasive flow into the compressed air stream. When the angle of feed valve is 45^0, the abrasive merges and mixes uniformly with the compressed air stream.

Blast Hoses and Nozzles:

The blast hoses convey the compressed air-abrasive mixture from the blast pot to the nozzle. Lowering the diameter of the hoses can increase the pressure drop significantly and hoses of inside diameters greater than 1 in. (preferably 1.25 inches) have been recommended for industrial operations. Couplings used in the air supply streams must be designed to allow smooth transition between hoses and fittings. The couplings must also include automatic safety connections. The length of the blasting hose must me as small as possible to reduce pressure loss due to friction.

Blasting nozzles are available in various configurations and lengths. Nozzle selection depends on (a) nature of surface to be cleaned, (b) overall size of the blasting job, (c) compressed air availability, and (d) abrasive type. The pressurized abrasives reaching the nozzle are accelerated and dispersed uniformly in a high velocity pattern. Long venturi type nozzles provide higher velocities and a more uniform blasting pattern than straight barrel type nozzles. Outer jackets of the nozzles are commonly made of aluminum, zinc die metals, steel or urethane and inner liner materials are manufactured from ceramics (wears off easily), tungsten carbide, boron carbide or silicon carbide. Tungsten and silicon carbide lined nozzles result in longer nozzle lives, consistent air, abrasive supply, and are relatively inexpensive. Outer jackets made of polyurethane result in impact protection and reduction in overall nozzle weight making it easy to handle. Size of blasting job, surface type and accessibility of the blaster to the surface are three factors driving the choice of nozzle length. Longer venturi nozzles are found to be most efficient on steel surfaces with rust, mill scale and paint as surface contaminations.

2.1.2 Abrasives

The primary factors involved in the choosing and abrasive for a particular blasting job include (a) scope of job, (b) job location, (c) initial surface contamination, (d) final surface profile, (e) productivity or cleaning speed of an abrasive, (f) material consumption rate, and (g) potential of atmospheric emissions. The factors that affect the performance of an abrasive are its hardness, shape, size and cleanliness.

Friability and abrasive breakdown rate are governed by its friability. The harder the abrasives, the easier they pulverize on impact. When the profile required is very deep or the surface has high tenacity, harder abrasives are used.

Surface profile and etch are determined by the shape of abrasives used. Deep profiles are produced by angular sharp particles whereas round particles are used to blast slowly and to produce a shallower profile. Shape of the abrasives has been found to impact productivity more than other properties.

Size of the abrasive has impacts on the profile created and the resultant particulates emitted into the air as a result of blasting. Coarser particles are found to give deeper profiles than fine ones.

Cleanliness of abrasives can be improved by processing them before use. They can be screened and washed to remove contaminants, dust or finer fractions of particulates. Dust and fine fractions interfere with final desired finish and can reduce productivity.

2.1.3 Operator skill level

The overall process efficiency and productivity of blasting are controlled by the operator who carries out the blasting (blaster). Cost of labor is one of the primary components of overall process life cycle costs of blasting and it can be as high as the equipment and supplies cost. It is necessary to train blasters on equipment handling, blasting techniques, safety, surface profile control, standards for surface cleanliness, and health related issues [2].

2.2 Factors Affecting Blasting Performance

Estimating productivity, consumption and emission rates from blasting is difficult in spite of careful consideration to the essential components. This is because of the high variability of system set up, initial and final surface contaminations, worker skill, abrasive characteristics and most importantly the environmental conditions which make any calculation a mere estimate. The following are some of the factors that influence the productivity, consumption and emissions from blasting.

2.2.1 Abrasive type

The type of abrasive used and its properties (friability, density, shape, size, hardness and cleanliness) affect the productivity, consumption and emission rates. Abrasive density is linearly related to consumption. Productivity is affected primarily by abrasive shape and size as described in the previous section. Abrasive mixtures containing higher proportions of smaller particles perform more work than those with higher concentrations of coarser fractions. To achieve desired surface finish, working mixtures containing abrasive particles of all sizes are used. A 30% decrease in productivity can be observed between a low profile and a medium profile working mix and a 50% drop from medium to high (coarse) profile mix.

2.2.2 Initial and final surface conditions

Productivity, consumption and emissions are influenced by the desired profile, quantity and nature of initial surface contaminants (rust, paint, oil, grease, mill scale, etc). Selection of profile depth influences the choice of abrasive, productivity, consumption and emissions. Lower profiles result in higher productivities. A higher profile results in higher abrasive consumption rates.

Desired degrees of cleaning and profile have a direct influence on production rates. The Society for Protective Coatings formerly Steel Structures Painting Council (SSPC) has provided information on surface preparation, selection and applications of coatings, environmental regulations, as well as health and safety issues pertaining to the protective coatings industry. Definitions of some of the general types of surface preparations (SP) used in shipyards are given below:

SSPC – SP 5 (White Metal Blast Cleaning): is defined as the surface with a gray-white, uniform metallic color, slightly roughened to form a suitable anchor pattern for coatings. SSPC – SP5 surface is shown in Figure 2.

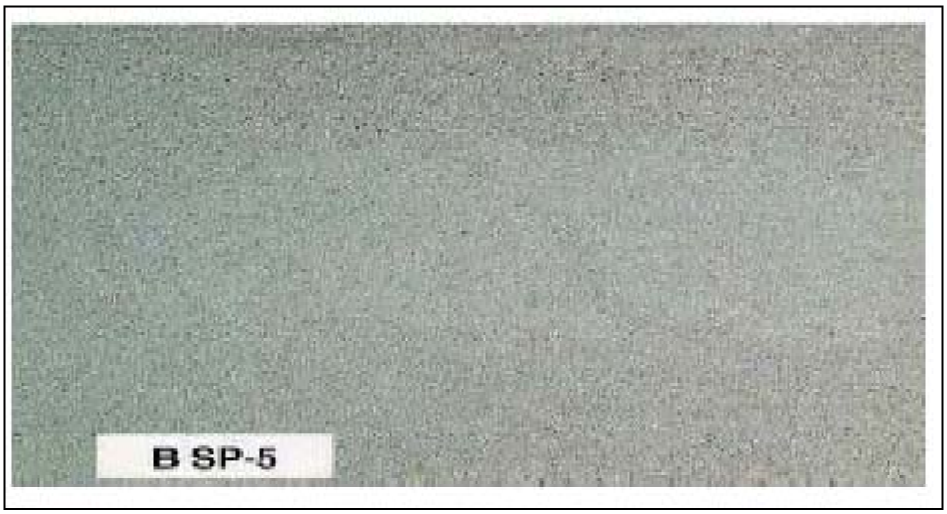


Figure 2 SSPC – SP5 Surface Finish, Source: The Society for Protective Coatings

SSPC – SP 6 (Commercial Blast Cleaning): is defined as one from which all oil, grease, dirt, rust, mill scale and old paint have been completely removed except for slight shadows, streaks or discolorations caused by rust stain, mill scale oxides or slight, tight residues of rust or paint may be found in the bottom of pits; at least 2/3rd of each square inch of surface area shall be free of all visible residues and the remainder shall be limited to light discoloration, slight staining or tight residues mentioned above. The commercial blast finish is shown in Figure 3.

Figure 3 SSPC – SP6 Surface Finish, Source: The Society for Protective Coatings

SSPC – SP 7 (Brush-off Blast Cleaning): A brush-off blast cleaned surface is defined as one from which all oil, grease, dirt, rust scale, loose mill scale, loose rust and loose paint are removed completely but tight mill scale and tightly adhered rust, paint and coatings are permitted to remain provided that all mill scale and rust have been exposed to the abrasive blast pattern sufficiently to expose numerous flecks of the underlying metal fairly uniformly distributed over the entire surface.

SSPC – SP 10 (Near-White Blast Cleaning): is defined as one from which all oil, grease, dir, mill scale, rust, corrosion products, oxides, paint or other foreign matter have been completely removed form the surface except for very light shadows, very slight streaks or slight discolorations caused by rust stain, mill scale oxides, or light, tight residues of paint or coating that may remain [10]. Figure 4 shows the near white blasting finish.

Figure 4 SSPC – SP10 Surface Finish, Source: The Society for Protective Coatings

2.2.3 Blast pressure

Though it was believed that productivity increases with blast pressures, this trend was not found uniformly for all abrasives and all scenarios. In industries usually pressure is set the highest value supported by the air compressor. Research has shown productivity decreases for blast pressures over 100 PSI. The kinetic energy of the abrasive particles responsible for achieving blasting and removal of surface contaminants is given by

$$KE = \frac{1}{2} m V^2 \qquad \text{--- (1)}$$

Where, KE = kinetic energy of the abrasive particles (N)

m = mass of particles (kg)

V = particle velocity (m/s).

The velocity of the particles is determined by the blast pressure. Particles with such high energies while hitting on the surfaces breakdown into smaller particles resulting in release of airborne particulates. Rust, mill scale, paint chips and other surface contaminants also breakdown and become airborne. Friability of abrasives as discussed earlier influences the breakdown rate of abrasives thereby influencing particle emissions.

Lower blast pressures result in lower particle velocities resulting in productivity and particulate emissions. It is important to maintain proper/optimum pressure since lower pressures result in lower velocities and thus reduce productivity while consuming more material. At higher pressures, particles achieve higher velocities and their breakdown rate increases thereby increasing emissions as well as productivity. Very high pressures will also reduce productivity and increase consumption as the particles undergo more damage at higher velocities resulting in higher emissions [2,11,12]. Air flow at the blast nozzle increases with blast pressure. With the increase in airflow, more particles are inducted into the air stream resulting in higher productivity. Hence higher productivities, lower consumption, emission rates and costs can be obtained by increasing the pressure till a threshold value. A lean mixture of air and abrasive has been found to be more productive than a rich mixture. Air pressure also increases the surface profile obtained [13]. At higher pressures, particle rebound rate is higher resulting in a lesser mass flux of particles reaching the substrate. Also, at higher pressure, back pressure on the abrasive hose increases dramatically, causing difficulty to the blaster and loss of productivity [14]. Higher wind speeds increase emissions by enhanced ventilation of the process and by retardation of coarse particle deposition.

2.2.4 Abrasive feed rate

The abrasive feed rate is varied using metering valves located at the bottom of the blast pot. From equation (1), it can be seen that the mass of the abrasive particles hitting the substrate is proportional to the abrasive feed rate. Increasing the feed rate results in increase in productivity and higher particle breakdown thus increased particulate emissions. On the other hand, increasing the feed rate beyond a certain extent can decrease the productivity. This is because at high feed rates settings, abrasive particles tend to collide with particles that have once hit the surface and are rebounding. This results in lesser number of particles actually reaching the surface (lesser particulate flux as described in the previous section) and therefore in decreased productivity, increased abrasive consumption, and increased particulate emissions. When the material flow is more uniform and moderate, consumption and particulate emissions are lower. This results in increase in productivity at lesser consumption rates [10]. Abrasive flow into the compressed air stream is extremely critical and very precise metering valves need to be used to control the actual material flow rate. In industries, the feed valve is adjusted based on the blaster's judgement about uniform material flow at the nozzle. Unfortunately, most blasters do not have sufficient knowledge of correct air-abrasive mixture and of accurate metering valve adjustments for providing the exact abrasive flow rate. As mentioned in the previous section, when the air abrasive mixture is rich, insufficient energy is available to accelerate the particles to high velocity to achieve reasonable productivity levels. It also results in pressure drop owing to an excess amount of abrasive in the hose which causes particle interference in the blast hose [13]. Hence, it can be clearly observed that blast pressure and abrasive feed rate act synergistically and influence the productivity, consumption and atmospheric emissions from dry abrasive blasting process.

2.2.5 Nozzle type

Commercially available nozzles are categorized based on nozzle geometry as follows:

Straight Bore Nozzles are those that have a constant orifice diameter for the whole nozzle length

Venturi Nozzles are those that converge to the nozzle's size at a point approximately half of the nozzle's length and then diverge for the reminder of the nozzle. Acceleration of the air abrasive mixture and increase in impact energy occur at the converging portion of the nozzle. Hence, increased productivity is achieved by using this geometry. The diverging portion of the nozzle results in an increase in blast pattern [10].

2.2.6 Nozzle size

Historically it was believed that productivity increases with nozzle size. Depending on the friability of the abrasives nozzle size increase is expected to increase productivity at higher blast pressures. Increase in nozzle size increase the actual abrasive flux to the target substrate thus increasing the cleaning rate (productivity) at higher pressures using lesser material quantities [13]. Nozzle orifice diameters vary from 1/8 inch to ½ inches in increments of 1/16 inches. Though productivity increases with nozzle size, the limiting factor is the amount of compressed air required to achieve high productivity at higher material flow rates. For example, for a given blast pressure, each 1/16 inch increment in nozzle diameter requires twice as much as flow [10]. Nozzles should ideally be operated at or above the design pressure and the smallest useable abrasive size should be chosen to achieve high productivities and low consumption rates [15].

2.2.7 Standoff distance

The distance between the tip of the blast nozzle and the substrate surface is called standoff distance. Standoff of distance is critical achieve uniform flow, high particulate flux reaching the metal surface, desired blast pattern and productivity. Larger stand off distances results in larger blast patterns and smaller distances are required to remove tightly adherent surface contaminants. Stand off distances range from 6 to 24 inches [10].

2.2.8 Angle of attack

The angle between the nozzle and the substrate is defined as the angle of attack. Commonly used angle of attack ranges between 60^0 and 120^0. Holding the nozzle perpendicular to the substrate (angle of attack = 90^0) results in more impact energy removing tightly adherent surface contaminants. Surface scouring of the substrate can occur with blast nozzles less than 90^0. Hence, angle of attack affects the profile obtained, final surface finish, cleaning rates and hence the productivity and consumption [10].

2.2.9 Dwell time

Dwell time is defined as the amount of time required to achieve the desired surface finish and cleanliness before moving the nozzle to the next area (or point) on the target metal surface. Dwell time is influenced by the blast pattern (smaller the blast patterns shorter is the dwell time). Blaster expertise is mandatory to reduce dwell time and increase productivity [10]. The sum of dwell times at all the blasted locations on a metal surface is defined as the total blasting time.

2.3 Health Effects and Environmental Impact of Blasting

Solid wastes (spent abrasive, surface contaminants and other materials) as well as airborne emissions are generated by dry abrasive blasting process [16,17]. Dry abrasive blasting is associated with a significant number of occupational diseases: silicosis, a respiratory disease caused by inhaling of fine dust containing quartz or respirable free silica, and noise induced hearing loss owing to excessive noise exposure during the process. Blasting of panels painted using lead based panels creates occupational health concerns related to lead exposure. Human health hazards associated with blasting include physical injury from the abrasive projectile stream, respiratory hazards from abrasives and target materials, and noise from the air supply inside the blaster's helmet and outside from the blasting activities. Personnel standing besides the blast pot or other site workers are generally also exposed to dust and significant (excessive) noise levels. Solid wastes and air emissions from blasting can translate to environmental contamination as a result of environmentally sensitive contaminants in the blast media (lead, radioactive substances), and from lead on painted structures. If the blast media contains radioactive material (for example, thorium from monazite contamination), radiation exposure hazards are likely to blasting and other personnel in the facility [becomes 16, 17]. A study by Carlson in 1990 confirmed the environmental significance of blasting as well as its potential effect on workers other than the abrasive blasting operator [18]. Industries tend to compromise of health risk and safety related issues to reduce overall process life cycle costs.

Particulate emissions from dry abrasive blasting pose significant concerns due to the health effects, visibility and hearing impairment, imbalance in ecosystem and aesthetic damage. Research has demonstrated that inhalation of particulate matter causes respiratory problems, asthma, chronic bronchitis, and deterioration of lung functioning. Size of particles emitted plays a significant role in adverse health effects [19]. As mentioned earlier the USEPA designated PM sizes into ultrafine, fine and coarse based on aerodynamic particle diameter. Of these fractions, the health effects of fine and ultrafine fractions are significantly greater on respiratory system and lung functioning as the finer fractions are absorbed better in the respiratory tract and lungs better than the coarser ones [19-26]. Once ultrafine particulates get deposited on the walls of the lungs, toxic compounds associated with PM are released faster than fine and coarse particles. Dry abrasive blasting emits particles of various sizes, particulate metals such as arsenic, cadmium, chromium (trivalent and hexavalent), lead, manganese, nickel, titanium and others [27-30].

Metal concentrations in the spent abrasive streams were found to exceed the Toxicity Characteristic Leaching Procedure (TCLP) criteria limits [31]. The study of consumption rates (which directly corresponds to spent abrasive quantities generated) and emission rates is critical in worker exposure and air quality assessment studies owing to the toxicity of these metals. Estimation of concentration, particle size distribution and chemical composition of particulate matter (PM) is necessary to understand their health effects. Estimation of hourly and annual PM emissions is important to study the impact on human health and environment. Concentrations and characteristics of atmospheric PM emissions from dry abrasive blasting depend on abrasive material (its size, shape and chemical composition), surface cleaned, and process conditions [19, 32, 33]. Studies have also shown that different abrasives have different pulmonary toxicities [34].

2.4 Available Literature on Blasting Performance

Available literature on productivity and consumption is very limited, subjective and incomplete. Abrasive manufacturers provide average or wide-ranging values for productivity and consumption of abrasives. Research was conducted on evaluating the productivity and consumption of various abrasives but at a few selected pressure, feed rate conditions and using nonstandard estimation techniques [28,35,36]. Research conducted by the US Army Corps of Engineers on painted surfaces provided an average value for a particular operating condition [37]. It has been found that conventional dry abrasive blasting results in an average productivity of 100 sq.ft/hr [38] but such estimates cannot be used for all scenarios (different abrasives, operating conditions).

Emission factor literature too is incomplete, discontinuous and subjective. The National Shipbuilding Research Program (NSRP) conducted a research on some of the most commonly used abrasives at blast pressures of 80 and 122 PSI for PM_1, $PM_{2.5}$, PM_4 and PM_{10}. Although this document provides emission factor data, the method of emissions estimation was based on mass-balance method rather than actual stack sampling methods and emission factors are not available for any intermediate pressures. Research conducted at Halter Marine Ship repair facility in 1999 used a mass balance approach and several assumptions to estimate the total emissions collected at the end of the process which lacked data quality. The study used two pressures (80 PSI and 122 PSI) [35]. The Southwest Research Institute carried out a study in 1993 to estimate particle size distribution and spent abrasive generation from blasting of painted steel surfaces. Blasting process was automated at a fixed productivity and two pressures only. Particle size distributions were determined using sieve and coulter counter analysis. The major drawback of this study was that particles captured in the filter bag were measured and no stack sampling was done, thus the results did not account escaped fine particles. Hence, the emission factors and the particle size distributions obtained may not represent true emissions [39].

Various state agencies reported general emission factors for total PM, PM_{10} and $PM_{2.5}$ for garnet, coal slag, sand, metallic grits, and mineral slags but did not specify the process conditions or surface type. Texas, California, and the County of San Diego Air Pollution Control District have reported emission factors for TPM and some PM fractions for sand, metallic, grit, slag, and mineral abrasives. The available data was combined to produce emission factors for abrasive blasting without actually specifying media type used. The emission factors reported are 0.027, 0.013, and 0.0013 lbs of emissions/lbs of abrasive used for TPM, PM_{10} and $PM_{2.5}$ respectively. These clearly indicate that there is limited emission factor data applicable for dry abrasive blasting operations. The California Air Quality District, the Bay Area and South Coast Air Quality Management Districts have reported emission factors of 0.01 lbs of PM_{10} emissions/lb of metallic shot or grit abrasives. The county of San Diego has reported 0.0038 lbs of total PM /lb of abrasive consumed. The USEPA has compiled the AP-42 emission factor document for Total PM (TPM), PM fractions and particulate metals from different research studies based on varied experimental conditions and diverse test procedures. The environmental parameters and test conditions were highly variable, and emission measurements were not standardized. Owing to all these reasons, the results lack data quality ranking according to EPA. Hence the available literature data for uncontrolled total PM emission factors is subjective, discontinuous, and unreliable [4,5,16,17,40 – 43].

It can be clearly seen that, in the currently available literature, discrete datasets are available for performance parameters; there has not been efforts to estimate or model the performance parameters over the commonly observed ranges in the industry. Moreover, these data sets are subjective in nature owing to the variability in experimental conditions and environmental variables. Also, the simultaneous variation of the performance parameters with important process variables such as blast pressure and abrasive feed rate has not been studied exhaustively. The tests carried out in the past were done using non standard experimental procedures. Hence, the *Air Quality and Particulate Matter Research Team* at the University of New Orleans initiated research in 2002 to carry out enclosed blasting experiments, develop data and models for productivity, consumption and emissions from abrasive blasting of steel panels using six abrasives at commonly used process conditions. In the first phase of the research, the surface contamination was *flash rust* (obtained by allowing the plates to rust under the action of air and moisture for 24 hours) and the abrasives studied were coal slag, garnet, copper slag, barshot, specialty sand and steel grit [49,50]. Productivity, consumption and uncontrolled TPM emission factors data was generated and two-dimensional mathematical models were developed expressing performance parameters as function of blast pressure (at a given feed rate) and feed rate (at a given blast pressure). However, this study was limited to flash rusted panels and did not consider marine paint as surface contamination. Moreover, the models developed were two-dimensional (for example of productivity variation with feed rate at a given pressure, etc). Multivariable regression analysis models to express the simultaneous influences of process variables (pressure and feed rate) on performance parameters were not developed.

3.0 Objectives

3.1 Need for Research

The USEPA, NSRP, the Office of Naval Research (ONR), and many other private and governmental agencies have funded research in the past to the process and parameter interactions. As discussed earlier, productivity, consumption and emissions, concentration, size fractions, and composition of total PM emitted from blasting depend on

(a) Blast pressure,

(b) Abrasive flow rate governed by the feed valve setting,

(c) Abrasive properties (shape, size, and hardness),

(d) Recyclability of the abrasive,

(e) Nozzle size,

(f) Stand off distance (between the surface and blast nozzle),

(g) Angle of attack (angle between surface and nozzle), and

(h) Exhaust fan capacity in case of enclosed spaces / wind velocity in case of open air blasting.

Of these parameters, initial surface contamination, blast pressure and abrasive feed rate are the most critical ones influencing productivity, consumption and the quantities and composition of total PM emissions. More importantly, pressure and abrasive feed rate have simultaneous and synergistic influences on the performance parameters [40].

Currently abrasives are chosen merely based on application, costs and few other thumb rules. Industries need a way to know that a particular abrasive functions best for a particular application at a particular pressure and feed rate conditions, so that they can use the abrasive at those conditions to increase productivity, reduce consumption and there by solid waste generation, emissions and costs. This is not totally achievable for all abrasives with the available literature data. This is because productivity, consumption and PM emissions data is not available for all abrasives at commonly used process conditions.

For a given nozzle pressure, there is no a single continuous function that relates the performance parameters and abrasive feed rate so that to achieve a desired productivity or consumption or emission levels, the metering valve can be opened accurately. Similarly, continuous functions expressing performance parameters as functions of blast pressure. Though discrete datasets are available for performance parameters (productivity, consumption, and atmospheric PM emissions),

1. Available data is incomplete and subjective (owing to variability in experimental conditions and environmental variables) to completely understand the performance of commonly used abrasives,
2. Very limited simultaneous observations on performance parameters (for the same blast pressure and abrasive feed rate) have been made to-date for commonly used abrasives,
3. Variation of these performance parameters with process parameters (pressure and abrasive feed rate) has not been studied exhaustively
4. Standardized testing protocols have been used neither for estimating performance parameters nor their relationships with process parameters.

To address these issues, the *Air Quality and Particulate Matter Research Team* at the University of New Orleans initiated research in 2002 to carry out enclosed blasting experiments, develop data and models for productivity, consumption and emissions from abrasive blasting of steel panels using six abrasives at commonly used process conditions. In the first phase of the research, the surface contamination was flash rust and the abrasives studied were coal slag, garnet, copper slag, barshot, specialty sand and steel grit [49,50]. Productivity, consumption and uncontrolled TPM emission factors data was generated and two-dimensional mathematical models were developed expressing performance parameters as function of blast pressure (at a given feed rate) and feed rate (at a given blast pressure). However, paint as a surface contamination was not considered in the first phase nor was it attempted to obtain three dimensional models to express the simultaneous influences of process variables (pressure and feed rate) on performance parameters. The scope of this dissertation includes

1. Evaluation of productivity, consumption and uncontrolled TPM emission factors for a group of three recyclable abrasives: garnet, barshot and steel grit/shot on painted steel panels
2. Data analysis using multiple regression to study the influence of pressure and feed rate on performance parameters
3. Development of predict models to determine productivity, consumption and uncontrolled TPM emission factors as function of process parameters

3.2 Objectives of Research

The specific objectives of this research were to:

- Analyze commercially available paints used in the maritime industry and select a paint for painting the test panels,
- Study the industrial and environmental performance of three recyclable abrasives: garnet, barshot and steel grit/shot,

- Simulate enclosed blasting operations on painted panels and estimate performance parameters at operating conditions commonly used in industries through standardized experimental procedures recommended by the USEPA,
- Estimate the performance parameters namely:
    - ***Productivity:*** defined as area cleaned per unit time expressed in m^2/hr,
    - ***Consumption:*** defined as mass of abrasive consumed per unit area cleaned expressed in kg of abrasive used / m^2 area cleaned,
    - ***Uncontrolled TPM Emission Factors:*** defined in two ways as follows
        - mass of total particulate mass emitted per unit area cleaned expressed in kg TPM emitted / m^2 of area cleaned,
        - mass of total particulate mass emitted per unit mass of abrasive consumed (kg TPM emitted / kg abrasive consumed),

    These emission factors are uncontrolled emission factors wince no air pollution control device was used to control these emissions.
- Analyze the experimental results and develop various two and three dimensional mathematical models to estimate/predict (1) productivity, (2) consumption, (3) uncontrolled TPM emission factors based on blast pressure and abrasive feed rate for painted panel, and
- Rank the three abrasives based on industrial and environmental performance.

4.0 Materials and Methods

4.1 Research Approach

As discussed in detail in the literature review section, the process parameters found to influence productivity, consumption and TPM emission factors from dry abrasive blasting process are (a) blast pressure, (b) abrasive feed rate, (c) properties of abrasive (size, shape, and hardness), (d) number of reuses of the abrasive, (e) nozzle size, (f) angle between blast nozzle and blasted surface, (g) stand-off distance, (h) ventilation conditions / exhaust fan capacity in case of indoor blasting, (i) wind speed in case of outdoors, and (j) worker expertise. It was mentioned earlier that the NSRP demonstrated that blast pressure and abrasive feed rate are the two most important parameters that process performance. The aim of this dissertation was to understand these relationships better, and quantifying them by varying one parameter (blast pressure or abrasive feed rate) at a time within the commonly observed range in industry. This approach facilitated the evaluation of the effect of blast pressure on performance parameters at a particular feed rate and the effect of abrasive feed rate on performance parameters at a particular blast pressure.

The common blast pressure range used in industries is between 80 to 120 PSI because blast pressures less than 80 PSI are not very productive and pressures over 120 PSI are not safe with the commercially available blast equipment. To observe productivity, consumption and TPM emission factor trends at a given feed rate, experiments were conducted at three blast pressures to obtain a continuous function. Similarly, the Schmidt valve was set at three distinct feed rate settings at a given pressure to obtain a continuous function with respect to feed rate. Thus, experiments were carried out at three blast pressures (80, 100, and 120 PSI) and three feed rate conditions: 3, 4, and 5 turns of opening of Schmidt valve for garnet and barshot, and 1.5, 3, 4.5 turns for steel grit/shot (as per manufacturer's recommendations). For each set of pressure and feed rate tested, three repetitions of the same experiment were performed to ensure the repeatability of the process and results. This resulted in nine combinations of operating conditions (3 pressures x 3 feed rates), and hence a total of 27 total runs for each abrasive. Field experiments were designed keeping all other parameters constant and varying blast pressure and feed rate as above to ensure uniformity of test conditions.

4.2 Abrasives Studied

The three recyclable abrasives studied in this research were:

1. *Medium grade garnet* obtained from Barton Mines LLC,
2. *Medium grade barshot* obtained from Optaminerals Inc, and
3. *Medium grade steel grit/shot mixture* obtained from Wheelabrator Inc.

4.2.1 Garnet

Garnet is an iron, magnesium and aluminum silicate complex also called *Almandite* or *Pyrope* Garnet with a chemical formula: $(Fe, Mg)_3\ Al_2(SiO_4)_3$. Garnet contains 36% of SiO_2 and is a "low free silica" blasting media. It has been shown that Barton Garnet is void of all the toxic metals regulated by California's Title 22 hazardous waste standards. It has also been certified by California Air Resources Board (CARB) for dry unconfined blasting. Moreover, it meets all the current chemical limits mandated by USEPA, NIOSH and OSHA. Barton Garnet is one of the abrasives qualified for U.S. Navy specification MIL-A-22262B (SH). The density of the garnet used in this study is 3.9 – 4.1 g/cm^3. Garnet is recyclable for about five times resulting in lower material consumption rates. For the above said reasons, garnet is considered as a safer, more cost effective abrasive that results in outstanding surface preparation [44]..

Figure 5 Garnet Abrasive, Source: Garnet Mines Inc.

4.2.2 Bar shot

Specular hematite (commercially known as *barshot*), a chemically inert ferric oxide (Fe_2O_3) mineral, denser than other mineral or slag abrasives, is the raw material used in production of barshot abrasives. The crystalline state of this mineral is the most stable form of ferric oxide. As the particles are in a fully oxidized form, barshot does not rust, preventing clogging of the metering valves. Barshot is economical, recyclable, non-hygroscopic and non-magnetic. It results in efficient and speedy removal of old coatings, mil scale, etc. when used at higher pressures (120 PSI) leaving a near white (SP 6) to white metal (SP 10) preparation. Barshot is widely used by industries owing to its high productivity rates and lower dust generation potential at even high blast pressures (110-130 PSI). Barshot is therefore an important abrasive in surface preparation and polishing applications. Barshot results in high productivity and lower consumption as well as lower emission rates as compared to silica sand or coal slag [35]. It is commercially available in three grades: coarse, medium, and fine. Some commercially available abrasives are produced by mixing specular hematite with other abrasives. For example, Barshot ST© is obtained by mixing bat shot with steel shot. The advantages of barshot are its (a) cost effectiveness, (b) lesser consumption rates, (c) flat blast rates (density 183 barshot are its (a) cost effectiveness, (b) lesser consumption rates, (c) flat blast rates (density 183 lbs/cubic feet), (d) recyclability, (e) reduction in waste generation, (f) low dust generation, (g) reduction in total abrasive cost, labor, and disposal costs. Moreover, it does not contain measurable heavy metals, making it beneficial from an environmental perspective. Barshot results in minimum dust level as it contains less than 0.3% free silica. It is approved by California Air Resources Board Approved (CARB) Executive Order G-99-060. The density of the barshot used in the study is 5.4 g/cm^3 [45, 46]. Owing to all these factors barshot has been considered a lucrative abrasive, both, from the point of industrial performance and environmental friendliness.

Figure 6 Barshot Abrasive, Source: Optaminerals Inc.

4.2.3 Steel grit/shot

Steel grit is angular in shape and steel shot is round. Steel Grit is used for cutting granite blocks by gang-saws in granite industry. Steel Grit is very heavy in nature and possesses high density as compared to other materials. The density range of the studied abrasive is 6.8 – 7.4 g/cm^3. The angular edges of Steel Grit are sharp and the stability of the hardness of Steel Grit makes the cutting operation effective.

Figure 7 Steel Grit and Shot, Source: Chesapeake Inc.

The usefulness of Steel Grit and Shot are further improved by the fact that it can be recycled and reused for future blasting runs. Steel Grit can be recycled multiple number of times resulting in lowering of overall abrasive costs as well as reducing the amount of wastes to be disposed [46]. They have been found to have up to 50% higher productivity and provide better profile control. Steel abrasives can be made round (steel shot) or angular (steel grit) depending on the carbon composition. The common size ranges are 1 and 8 mm. Steel abrasives are manufactured by *atomizing* molten steel followed by thermal and mechanical treatments. Steel shot is manufactured from normalized, treated *hypereutectolde* steel and has the fine and homogenous structure of tempered *martensite* [47]. Steel grit is manufactured by crushing round shots. Their remarkable efficiency is due to the angular shape. Steel grit or shot, based on its type, can be reused between 500-5000 times [48].

4.3 Marine Paint and Thinner

The test plates used for blasting operations were painted with a 1:1 volume mixture of commercially available *Rustoleum© Safety Yellow* marine paint and thinner. The MSDS of the

Safety Yellow paint is provided in the Appendix section. Painting was carried out with a spray gun and hand roller. Sufficient time was allowed for the painted panels to dry before blasting. Paint thickness can be determined by the following equation [51]:

$$Coverage(ft^2) = \frac{(Gallonsused)x(1604\,ft^2 / gal / mil)x(Fractionvolumesolids)x(\%transferefficiency)}{FilmThickness(mils)} \quad \text{--(2)}$$

Transfer efficiencies are assumed to be in the range of 20-50% while using spray gun and 90% for roller application.

Area painted	= 40 ft^2
Volume of paint used for painting	= 250 ml
Fraction volume of solids (from paint MSDS)	= 0.529

The volume fraction of solids was assumed to be the same as weight fraction due to lack of data from paint MSDS sheets. Using the above formula, the paint thicknesses obtained were:

- 0.3 mils (for 20% efficiency),
- 0.76 mils (for 50% efficiency), and
- 1.3 mils (for 90% efficiency)

4.4 Emissions Testing Facility Design

This project was funded partially by USEPA Region 6, The Office of Naval Research (ONR) and The Gulf Coast Region Maritime Technology Center (GCRMTC). The tests were conducted at the emissions test facility adjacent to the Engineering Building at University of New Orleans main campus in New Orleans. The test chamber had dimensions 12 ft x 10 ft x 8 ft and was designed as per the guidelines of EPA method 204. The chamber was constructed using PVC sheets which were connected and riveted firmly to the floor. The floor was constructed using seasoned wood treated with waterproofing materials. Gaps were sealed with silicone to prevent any seepage of the water that could interfere with the test process. The blast chamber was equipped with sufficient internal lighting to aide the operator. Provisions were made to allow make-up air to enter the test chamber and the airborne particles were exhausted through a variable speed fan. The fan had a maximum volumetric flow rating of 5000 cfm. Emissions from the blast chamber were vented through a horizontal duct of one-foot diameter. A two-stage particulate collection system was located downstream of the duct to collect the particulate emissions and prevent nuisance to the ambient environment. The design of the exhaust duct, ventilation systems, and fine and coarse particulate systems were done in accordance with USEPA source sampling guidelines for workplace air quality monitoring. A wooden ramp was used to move the panel cart in and out of the chamber smoothly before and after blasting. A tarpaulin shed was erected adjacent to the test chamber to house the sampling equipment and test aids. The schematic of the Emissions Test Facility at the University of New Orleans is shown in Figure 8.

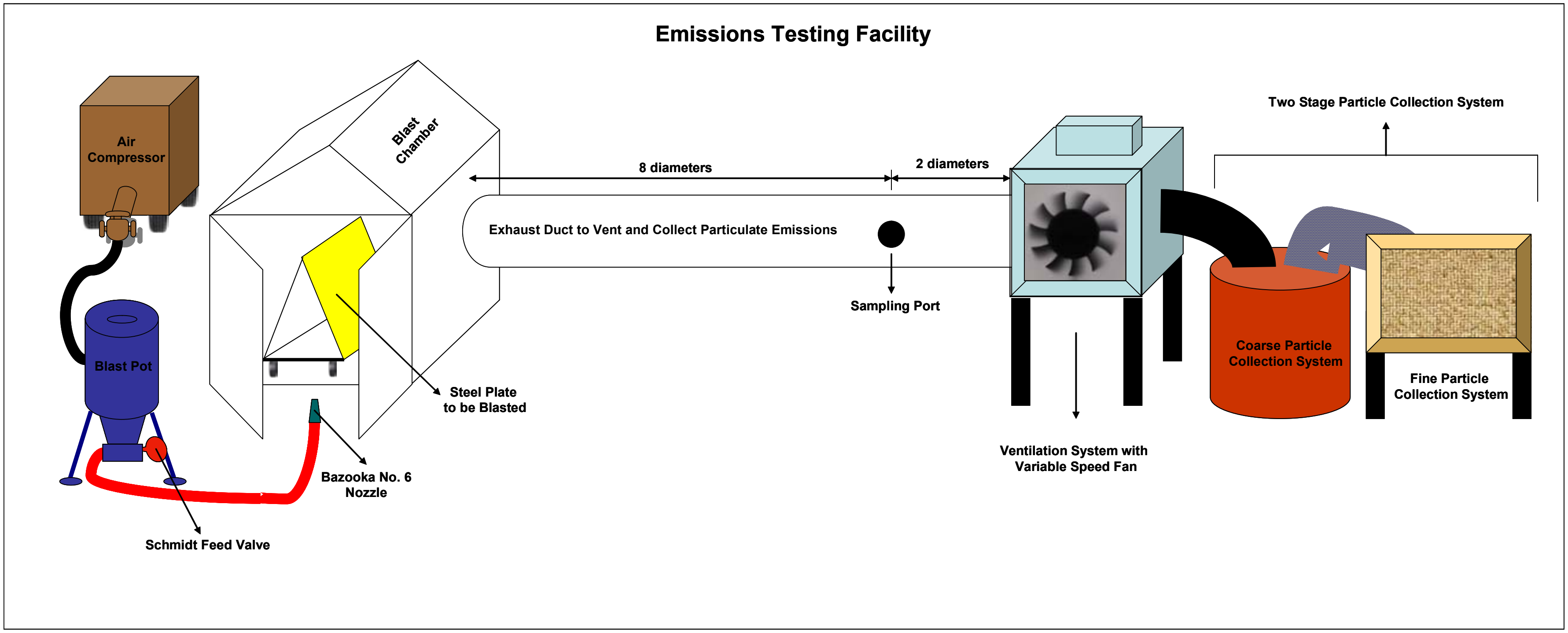


Figure 8 Emissions Testing Facility

4.5 Exhaust Duct

EPA method 1 for stack monitoring and testing was used to design the exhaust duct. The diameter of the exhaust duct was 1 foot. A sampling port, located at a distance of 8 diameters from the exhaust window and 2 diameters from the variable speed fan to minimize the turbulence on the downstream end was used to carrying out TPM sampling according to USEPA stack test methods (40 CFR 60 Appendix A). The exhaust window is directly connected to the duct, which carries the emissions vented and collected by the exhaust fan. The inner portion of the duct was maintained smooth, straight and free of undulations.

4.6 Particulate Collection System

As mentioned earlier, the two stage particulate collection was located downstream of the exhaust fan to prevent particulate release into the ambient environment. The first stage collected the coarse particles by changing the direction of the gas flow. The second stage (a system of four fabric filter units) collected fine particles. Since TPM sampling was carried out right at source and before the particulate filtration system (located downstream), the emission factors reported in this dissertation correspond to uncontrolled TPM emission factors. The 2-stage particle collection system did not have any impact on the measured uncontrolled emission factors.

4.7 Blasting Equipment and Test Plates

Commercially available Abec© blast pot of total capacity 600 lbs (= 273 kg) was used in the blasting experiments. Four mild steel plates of size 8’ x 5’ were painted with the marine paint mixture described earlier and used as the substrate to be blasted. The painted plates were mounted on a mobile cart for ease of movement and were allowed to dry prior to blasting.

Sullair Model 375H© and Ingersoll Rand compressors were used as compressed air sources. Moisture traps were provided before the blast pot to ensure dry air supply to the latter. High pressure hoses of appropriate inside diameters were used as connectors from the compressor to blast pot, secondary air supply, and blast nozzle. Schmidt abrasive feed valve, fitted at the bottom of the blast pot was used to regulate the abrasive mass flow rate in the experiments. The valve could be opened from zero (closed condition) to 9.5 (completely open condition) turns. As discussed in the literature review section, venturi nozzles result in higher productivity, lower consumption and emissions and are commonly used by industries. Bazooka nozzles are wide throat nozzles with a large diverging exit bore and are suitable for use at higher pressures to yield up to 60% higher results at lesser consumption rates and are known for their excellent coverage and minimum back pressure [10,52]. A standard Bazooka number #6 nozzle was used in this research. Secondary air supply was provided to the blaster by using an air filter. The equipment used for blasting is shown in the Figure 9.

4.8 Stack Sampling Equipment

A Napp Inc. Model 31 Stack Sampler was used to carry out stack sampling, velocity, and temperature measurements as specified in 40 CFR Part 60 Appendix A Test Methods 1 through 5 [53 – 57]. The entire sampling train system included:

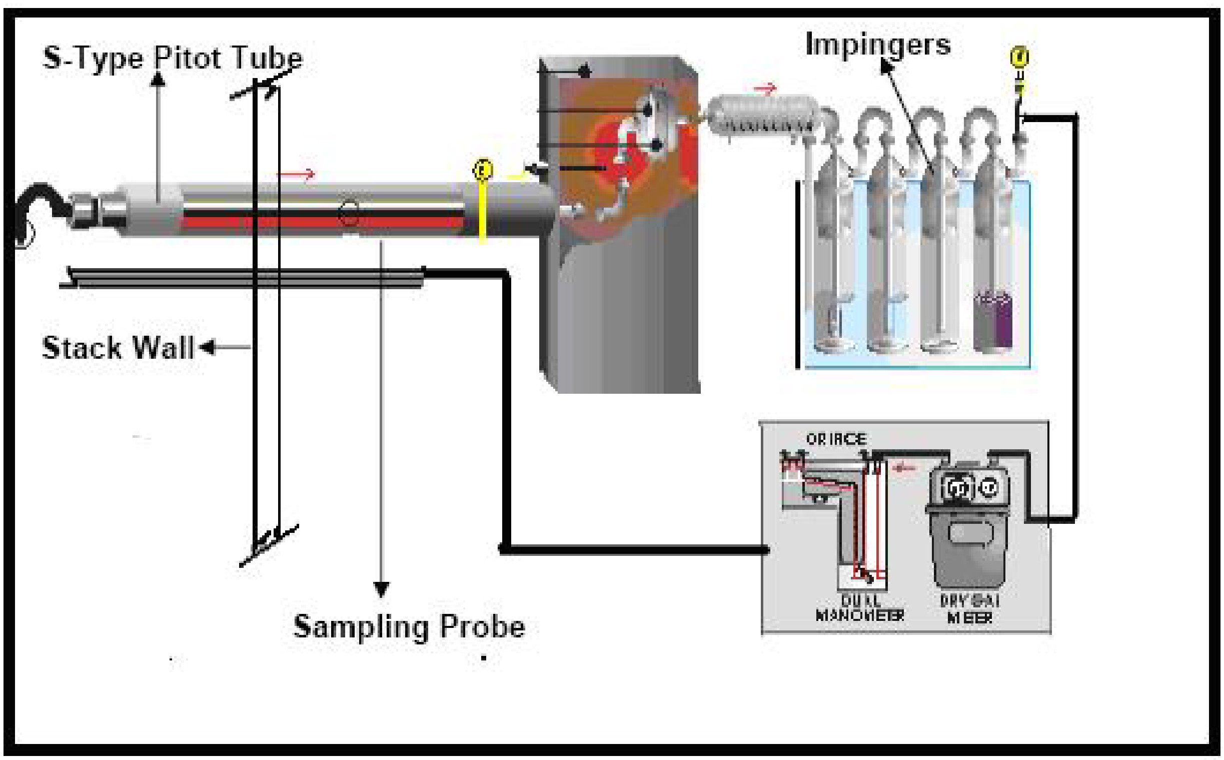
1. A heated probe consisting of
   i. A sampling nozzle,
   ii. S-Type pitot tube for velocity head measurements, and

Figure 9 Blasting Equipment (a) Blast pot, (b) Blast chamber and test plates mounted on mobile cart, (c) Schmidt valve, (d) Bazooka #6 nozzle, (e) Secondary air supply filter

iii. Stack temperature sensor,

2. Dry gas meter,
3. Differential pressure gauge for pressure measurements,
4. Filter holder to collect PM emissions on cellulose filters,
5. Hot box to house the filter holder,
6. Four glass impingers, and
7. Ice bath with crushed ice to house the impingers.

The sampling train in accordance with EPA Method 4 and 5 (for determining moisture content, evaluating the volumetric gas flow rate and TPM sampling) consisted of four glass impingers connected in series inside an ice bath to condense the water vapor. The first two impingers were filled with 100 ml of distilled water to allow the moisture to condense. The third impinger was left dry for further condensation. The fourth impinger contained known quantity of silica gel (adsorbent) to remove water vapor as the gas passed through it before entering the dry gas meter inlet [56]. The USEPA TPM sampling train assembly is shown in Figure 10. The sampling set up and equipment used in this research are shown in Figure 11.



Source: USEPA, 40 CFR 60, Appendix A

Figure 10 USEPA Method 5 Sampling Train for TPM Sampling

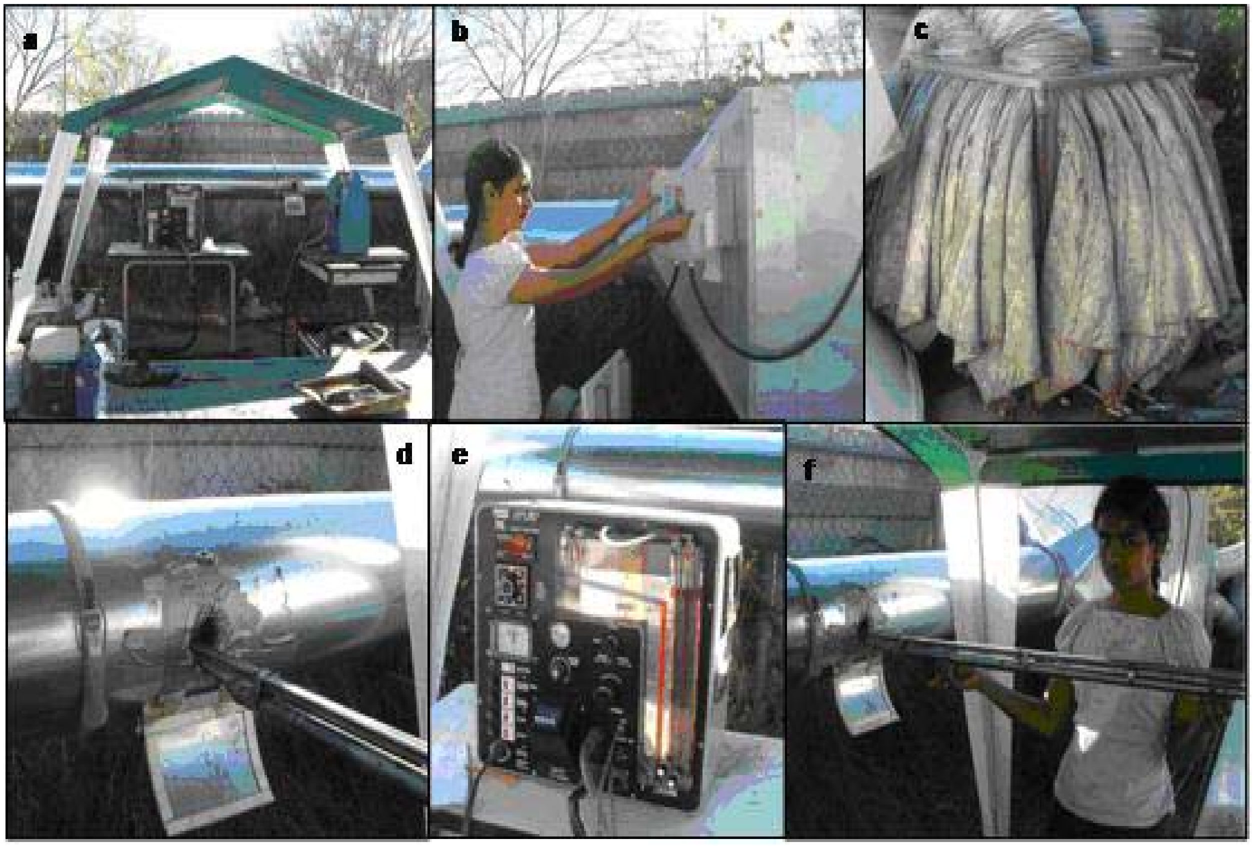


Figure 11 TPM Sampling Equipment (a) Stack sampling enclosure, (b) variable speed fan to vent particulate emissions, (c) particulate collection system, (d) stack and sampling port, (e) Stack sampling kit, (f) sampling in progress

4.9 Experimental Methodology

4.9.1 Enclosed blasting

For carrying out the blasting operations, three persons were trained by professionals on the operating procedures and safety issues. Near white (SP 10) finish was achieved in all the runs and the personnel were trained to visually examine and ensure this finish. A pre-weighed, known amount of abrasive was loaded into the blast pot through a sieve to remove any foreign material that may interfere with the smooth flow of the abrasive. Blast pressure was set by adjusting the compressor to provide the desired nozzle pressure measured by a needle gauge. The Schmidt feed valve was opening manually to set the abrasive feed rate (number of turns). The angle of attack and stand off distance were maintained 90^0 and one foot respectively in the all the experimental runs. The blasted area was measured using a measuring tape with appropriate approximations for non-quadrilateral geometries. The blasting time was recorded using a stopwatch.

4.9.2 TPM sampling

According to EPA Source Test Method 1, for a circular duct of one foot diameter, a total of eight traverse points were chosen for velocity and flow measurements [53]. The points were measured and marked on the sampling probe to ensure accuracy of measurements and ease of traverse. Pilot tests were conducted to determine the diameter of the sampling nozzle that would correspond to isokinetic flow conditions inside the duct. A nozzle with inner diameter of 0.18 inches was found to be appropriate for the study [56-60]. *Isokinetic sampling condition* means that the velocity of the sampled gas is equal to the velocity of the stack gas at the nozzle. If samples are not isokinetically, it will lead to incorrect sample volumes to be withdrawn from the stack resulting in incorrect TPM estimates. Hence, due care was taken to ensure isokinetic sampling conditions.

The exhaust fan was operated at 60 rpm and provided an air flow of 3000 cfm (average) throughout the course of study. Leak checks were performed along the sampling train to avoid gas leakage. Temperature and barometric pressure for the test days were noted from the local weather sources prior to testing. Particulate sampling was carried out at isokinetic conditions at the eight traverse points along the sampling duct while blasting was in progress inside the test chamber. The probe was sufficiently heated to prevent water condensation. The particles were collected through the nozzle on a pre-weighed Whatman No. 10 filter paper (conditioned by desiccation) to eliminate moisture. The hot box housing the filter assembly was maintained at a temperature of 120 ± 15°C to collect particulate matter from the sample gas stream, preventing any condensation of moisture. Velocity head and temperature measurements were carried out at the eight traverse points using the S type and the temperature sensors respectively. Static pressure in the stack, dry molecular weight of stack gas, sample volume, atmospheric pressure and temperature were recorded as per EPA guidelines. A series of four impingers was used to collect the moisture from the sampled gas. The first two impingers were filled with 100mL of water, the third impinger was left empty, and the fourth impinger was filled with 200-300 grams of silica gel. At the end of each experiment, the four impingers were weighed and increase in the weight was recorded to estimate the moisture content of the stack gas. The exhaust gas sample was sampled and collected for two minutes at each of the eight traverse points along the duct. Hence, the total sampling time for the entire duct was sixteen minutes for each run. Once the sample was collected, the filter paper was removed from the filter box, dried and conditioned by placing in a dessicator. Total particulate matter from the probe was collected in a beaker by rinsing the probe with acetone according to USEPA guidelines. The final weights of PM in filter paper and beaker were recorded after dessicating them for 24 hours. The sum of the weights of both containers was used to determine the actual mass of emissions in the stack gas. The spent abrasive from the chamber floor and the particulates collected in the two-stage particulate collection system were disposed off to landfills periodically. Experimental details namely, area and time measurements, stack sampling, and stack calculations according to USEPA methods have been included in the Appendix section.

4.10 Statistical Analysis

As the first step in statistical analysis of data, the mean and standard deviation were calculated for productivity, consumption and emission factors and these are tabulated in the results and discussion section. At each tested pressure and feed rate conditions, two dimensional mathematical models were developed to express performance parameters as function of abrasive feed rate and blast pressure respectively. These are presented in the figures in the *Results and Discussions* chapter for all the three abrasives.

One of the goals of the research is to express performance parameters in terms of blast pressure and abrasive feed rate. This was the second step in statistical analysis of the field data. This is a multiple regression statistical scenario with two independent variables and one dependent variable (productivity, consumption and TPM emission factors considered one at a time). Moreover based on physical evidence and explanations on how blast pressure and abrasive feed rate influence blasting performance, this is be clearly seen as a case of non-linear (polynomial) multiple regression.

Datafit© packaged supplied by Oakdale Engineering Inc was used to carry out the multiple regression analyses. The package typically fits the data into around 300 built-in multiple regression models and ranks them based on correlation coefficients. The statistical significance of the data, accuracy of the obtained models in predicting the actual field observations, and eventually the choice of the most appropriate model were done using the following criteria:

- Observed physical phenomena (relationship of blast pressure and feed rate to performance parameters)
- Best coefficient of determination (R^2)
- Continuous nature of the curve predicted by the model.

Definitions of the statistical parameters are given below:

$\text{Residual}_i = (Y_i - \hat{Y})$ -- (3)

$\text{Sum of Residuals} = \sum (Y_i - \hat{Y}_i)$ -- (4)

Closer the sum of residuals to zero, better is the fit.

$\text{Average Residual} = \sum (Y_i - \hat{Y}_i) / n$ -- (5)

Residual Sum of Squares (SSE) = $\sum (Y_i - \hat{Y}_i)^2$ -- (6)

Regression Sum of Squares (SSR) = $\sum [(\hat{Y}_i - \hat{Y}_i)^2 \text{ x } W_i]$ where $\sum W_i = n$ -- (7)

Hence, Total Sum of Squares (SST) = SSE + SSR, -- (8)

=> Coefficient of Multiple Determination (R^2) = SSR / SST -- (9)

SST measures the variation in observed response, SSR measures the “explained” variation and SSE measures the “unexplained” variation. Hence, R^2 measures the proportion of variation in the data explained by the regression model. R^2 of means 1 means that each and every point lies on the predicted curve.

The next step was the test the significance of the regression models using *two-way analysis of variance (ANOVA)* techniques. The p value or prob (t) value was calculated and the null hypothesis was rejected if the prob (t) < 0.05. The variance analysis procedure is summarized below:

	DF	**Sum of Squares**	**Mean Square**	
Regression	$p-1$	SSR	$SSR/(p-1)$	
Error	$n-p$	SSE	$SSE/(n-p)$	**F ratio** $= \dfrac{SSR/(p-1)}{SSE/(n-p)}$
Total	$n-1$	SST		

-- (10)

H_0: a = b = c = d = e = f = 0

H_1: atleast one of a,b,c,d,e,f, is non-zero.

If F ratio < 0.05, then reject H_0.

An F ratio of zero means that the probability of obtaining data equal to more extreme under the null hypothesis is zero. The next step was the test the significance of each coefficient using *t static*. In this case too, the null hypothesis (same as defined above) was rejected if Prob(t) < 0.05.

A basic assumption of the statistical analysis was that the data was normally distributed and this was verified by checking the residual plots. Plots of the residuals vs. predicted Y (if the residuals do not show any pattern, the data is normally distributed), and residual normality (Q-Q plot to check if the plot is a straight line for normal data) were made to verify this assumption. Also, plots of predicted values vs field observations were made.

The two and three dimensional plots, coefficients (for 99% confidence levels) in the model equation obtained using multiple regression analysis to predict productivity, consumption and uncontrolled TPM emission factors are presented in the *Results and Discussions* section. The statistical test details, Datafit© output, coefficients with the confidence intervals, scatter diagrams and residual plots are given in the appendix section.

5.0 Results and Discussions

Based on the field experimentation the performance parameters were calculated for each of the runs as follows:

1. ***Productivity = Area cleaned (m^2) / Blasting time (hours),***
2. ***Consumption = Mass of abrasive used (kg) / Area cleaned (kg/m^2),***
3. ***Uncontrolled TPM Emission Factor 1 = Mass of TPM emitted (kg) / Area Cleaned (m^2), and***
4. ***Uncontrolled TPM Emission Factor 2 = Mass of TPM emitted (kg) / Mass of abrasive used (kg/kg).***

These parameters are presented for barshot, garnet and steel shot/grit in Tables 1, 3 and 5 respectively. Tables 2, 4 and 6 show the statistical parameters (mean and standard deviation) for each of the nine tested conditions for the abrasives in the same order.

Table 1 Barshot: Field Data and Performance Parameters

Pressure	Feed Rate	Abrasive Mass	Blasting Time	Area	TPM mass	Productivity	Consumption	Emission Factors	
PSI	# turns	Lbs	min	sqft	G	m^2/hr	kg/m^2	kg/m^2	kg/kg
120	3	90	4	10	2378	13.94	43.95	2.560	0.058
120	3	70	4	10	2569	13.94	34.19	2.765	0.081
120	3	80	4	9.5	2319	13.24	41.13	2.627	0.064
120	4	90	6	20	3741	18.58	21.98	2.013	0.092
120	4	70	5	17	3292	18.95	20.11	2.084	0.104
120	4	80	5	17.5	3332	19.51	22.32	2.049	0.092
120	5	90	5	16	4836	17.84	27.47	3.253	0.118
120	5	80	4	12.5	3791	17.42	31.26	3.265	0.104
120	5	80	4	12.5	3797	17.42	31.26	3.269	0.105
100	3	85	5	9.25	2129	10.31	44.88	2.478	0.055
100	3	90	4	7.5	1864	10.45	58.61	2.675	0.046
100	3	90	6	11.5	2629	10.68	38.22	2.461	0.064
100	4	90	4	9.75	2074	13.59	45.08	2.290	0.051
100	4	80	6	15	2939	13.94	26.05	2.109	0.081
100	4	80	5	12.5	2596	13.94	31.26	2.236	0.072
100	5	90	5	11	3794	12.26	39.96	3.713	0.093
100	5	70	4	8.75	3024	12.20	39.07	3.721	0.095
100	5	80	5	11.25	3936	12.54	34.73	3.766	0.108
80	3	90	6	14.25	2862	13.24	30.85	2.161	0.070
80	3	80	5	12	2347	13.38	32.56	2.105	0.065
80	3	80	5	12.5	2397	13.94	31.26	2.065	0.066
80	4	90	4	13.75	2455	19.17	31.96	1.922	0.060
80	4	70	3	10.5	1845	19.51	32.56	1.891	0.058
80	4	80	5	17.5	2999	19.51	22.32	1.845	0.083
80	5	90	5	10	2351	11.15	43.95	2.531	0.058
80	5	70	5	10	2354	11.15	34.19	2.534	0.074
80	5	80	5	11	2548	12.26	35.52	2.493	0.070

All the runs were conducted in an enclosed chamber of size 12' x 10' x 8' ventilated with a fan operated at 60 rpm: average flow rate: 3000 cfm, blasting was conducted using number #6 nozzle

Table 2 Barshot: Statistical Parameters

Pressure	Feed Rate	Productivity			Consumption			Emission Factor 1			Emission Factor 2		
PSI	# turns	M^2/hr	Mean	SD	kg/m^2	Mean	SD	kg/m^2	Mean	SD	kg/kg	Mean	SD
120	3	13.94	13.70	0.40	43.95	39.76	5.03	2.560	2.651	0.105	0.058	0.068	0.012
120	3	13.94			34.19			2.765			0.081		
120	3	13.24			41.13			2.627			0.064		
120	4	18.58	19.01	0.47	21.98	21.47	1.19	2.013	2.049	0.036	0.092	0.096	0.007
120	4	18.95			20.11			2.084			0.104		
120	4	19.51			22.32			2.049			0.092		
120	5	17.84	17.56	0.24	27.47	29.99	2.19	3.253	3.262	0.008	0.118	0.109	0.008
120	5	17.42			31.26			3.265			0.104		
120	5	17.42			31.26			3.269			0.105		
100	3	10.31	10.48	0.19	44.88	47.23	10.40	2.478	2.538	0.119	0.055	0.055	0.009
100	3	10.45			58.61			2.675			0.046		
100	3	10.68			38.22			2.461			0.064		
100	4	13.59	13.82	0.20	45.08	34.13	9.84	2.290	2.211	0.093	0.051	0.068	0.015
100	4	13.94			26.05			2.109			0.081		
100	4	13.94			31.26			2.236			0.072		
100	5	12.26	12.33	0.18	39.96	37.92	2.80	3.713	3.733	0.029	0.093	0.099	0.008
100	5	12.20			39.07			3.721			0.095		
100	5	12.54			34.73			3.766			0.108		
80	3	13.24	13.52	0.37	30.85	31.55	0.90	2.161	2.110	0.049	0.070	0.067	0.003
80	3	13.38			32.56			2.105			0.065		
80	3	13.94			31.26			2.065			0.066		
80	4	19.17	19.39	0.20	31.96	28.95	5.75	1.922	1.886	0.039	0.060	0.067	0.014
80	4	19.51			32.56			1.891			0.058		
80	4	19.51			22.32			1.845			0.083		
80	5	11.15	11.52	0.64	43.95	37.89	5.30	2.531	2.519	0.023	0.058	0.067	0.009
80	5	11.15			34.19			2.534			0.074		
80	5	12.26			35.52			2.493			0.070		

All the runs were conducted in an enclosed chamber of size 12' x 10' x 8' ventilated with a fan operated at 60 rpm: average flow rate: 3000 cfm, blasting was conducted using number #6 nozzle

Table 3 Garnet: Field Data and Performance Parameters

Pressure	Feed Rate	Abrasive Mass	Blasting Time	Area	TPM mass	Feed Rate	Productivity	Consumption	Emission Factors	
PSI	# turns	lbs	Min	sqft	g	kg/hr	m^2/hr	kg/m^2	kg/m^2	Kg/kg
120	3	100	8	17	6496	340.29	11.85	28.73	4.113	0.143
120	3	100	6	13	5076	453.73	12.08	37.57	4.203	0.112
120	3	100	8	18	6199	340.29	12.54	27.13	3.707	0.137
120	4	100	8	20	8123	340.29	13.94	24.42	4.372	0.179
120	4	100	6	17.5	7119	453.73	16.26	27.91	4.379	0.157
120	4	50	4	10	4000	340.29	13.94	24.42	4.306	0.176
120	5	50	5	11.5	2104	272.23	12.82	21.23	1.970	0.093
120	5	50	4	10	1723	340.29	13.94	24.42	1.855	0.076
120	5	100	7	16	2848	388.91	12.74	30.52	1.916	0.063
100	3	100	7	15	3327	388.91	11.94	32.56	2.387	0.073
100	3	100	6	14	4174	453.73	13.01	34.89	3.209	0.092
100	3	50	4	10	2880	340.29	13.94	24.42	3.100	0.127
100	4	50	5	12	4095	272.23	13.38	20.35	3.673	0.181
100	4	50	5	12	4126	272.23	13.38	20.35	3.701	0.182
100	4	50	4	10	3455	340.29	13.94	24.42	3.719	0.152
100	5	100	6	11	3519	453.73	10.22	44.40	3.444	0.078
100	5	50	5	10	3205	272.23	11.15	24.42	3.450	0.141
100	5	100	8	16	4998	340.29	11.15	30.52	3.363	0.110
80	3	100	6	11.25	2698	453.73	10.45	43.41	2.582	0.059
80	3	50	6	9.5	2317	226.85	8.83	25.70	2.625	0.102
80	3	50	5	7.5	1804	272.23	8.36	32.56	2.589	0.080
80	4	100	7	18	6907	388.91	14.33	27.13	4.130	0.152
80	4	50	6	15	5859	226.85	13.94	16.28	4.204	0.258
80	4	100	6	15.5	6043	453.73	14.40	31.51	4.197	0.133
80	5	50	8	8.75	3397	170.15	6.10	27.91	4.180	0.150
80	5	50	4	4.5	1755	340.29	6.27	54.26	4.198	0.077
80	5	50	6	7	3743	226.85	6.50	34.89	5.757	0.165

All the runs were conducted in an enclosed chamber of size 12' x 10' x 8' ventilated with a fan operated at 60 rpm: average flow rate: 3000 cfm, blasting was conducted using number #6 nozzle

Table 4 Garnet: Statistical Parameters

Pressure	Feed Rate	Productivity			Consumption			Emission Factor 1			Emission Factor 2		
PSI	# turns	M2/hr	Mean	SD	kg/m^2	Mean	SD	kg/m^2	Mean	SD	kg/kg	Mean	SD
120	3	11.85	12.15	0.35	28.73	31.14	5.62	4.113	4.008	0.264	0.143	0.131	0.017
120	3	12.08			37.57			4.203			0.112		
120	3	12.54			27.13			3.707			0.137		
120	4	13.94	14.71	1.34	24.42	25.58	2.01	4.372	4.352	0.041	0.179	0.171	0.012
120	4	16.26			27.91			4.379			0.157		
120	4	13.94			24.42			4.306			0.176		
120	5	12.82	13.17	0.67	21.23	25.39	4.72	1.970	1.913	0.058	0.093	0.077	0.015
120	5	13.94			24.42			1.855			0.076		
120	5	12.74			30.52			1.916			0.063		
100	3	11.94	12.96	1.00	32.56	30.62	5.50	2.387	2.899	0.446	0.073	0.097	0.027
100	3	13.01			34.89			3.209			0.092		
100	3	13.94			24.42			3.100			0.127		
100	4	13.38	13.56	0.32	20.35	21.71	2.35	3.673	3.697	0.023	0.181	0.172	0.017
100	4	13.38			20.35			3.701			0.182		
100	4	13.94			24.42			3.719			0.152		
100	5	10.22	10.84	0.54	44.40	33.11	10.24	3.444	3.419	0.049	0.078	0.110	0.032
100	5	11.15			24.42			3.450			0.141		
100	5	11.15			30.52			3.363			0.110		
80	3	10.45	9.21	1.10	43.41	33.89	8.93	2.582	2.599	0.023	0.059	0.080	0.021
80	3	8.83			25.70			2.625			0.102		
80	3	8.36			32.56			2.589			0.080		
80	4	14.33	14.22	0.25	27.13	24.97	7.84	4.130	4.177	0.041	0.152	0.181	0.067
80	4	13.94			16.28			4.204			0.258		
80	4	14.40			31.51			4.197			0.133		
80	5	6.10	6.29	0.20	27.91	39.02	13.66	4.180	4.711	0.905	0.150	0.131	0.047
80	5	6.27			54.26			4.198			0.077		
80	5	6.50			34.89			5.757			0.165		

All the runs were conducted in an enclosed chamber of size 12' x 10' x 8' ventilated with a fan operated at 60 rpm: average flow rate: 3000 cfm, blasting was conducted using number #6 nozzle

Table 5 Steel Grit/Shot: Field Data and Performance Parameters

Pressure	Feed Rate	Abrasive Mass	Blasting Time	Area	TPM mass	Productivity	Consumption	Emission Factors	
PSI	# turns	Lbs	min	sqft	g	m^2/hr	kg/m^2	kg/m^2	kg/kg
120	1.5	50	3	5	636.5	9.29	48.84	1.370	0.028
120	1.5	50	3	5	745.9	9.29	48.84	1.606	0.033
120	1.5	50	3	6.25	977	11.61	39.07	1.683	0.043
120	3	50	3	7	815.2	13.01	34.89	1.253	0.036
120	3	50	4	9.75	1267.7	13.59	25.04	1.400	0.056
120	3	100	5	11.5	1639	12.82	42.47	1.534	0.036
120	4.5	50	2	4.5	1092.6	12.54	54.26	2.613	0.048
120	4.5	50	3.5	7.75	1725.7	12.34	31.51	2.397	0.076
120	4.5	100	5	10.5	2827.1	11.71	46.51	2.898	0.062
100	1.5	50	2	5	475.2	13.94	48.84	1.023	0.021
100	1.5	100	5	12.5	1066.7	13.94	39.07	0.918	0.024
100	1.5	50	3	7	674.8	13.01	34.89	1.038	0.030
100	3	50	2.5	7.5	867.2	16.72	32.56	1.245	0.038
100	3	50	3	8.75	1040.2	16.26	27.91	1.280	0.046
100	3	100	4	11.5	1468.6	16.03	42.47	1.375	0.032
100	4.5	90	5	5.25	1217.5	5.85	83.72	2.496	0.030
100	4.5	100	7	10	2546.4	7.96	48.84	2.741	0.056
100	4.5	50	3	4.5	957.4	8.36	54.26	2.290	0.042
80	1.5	100	5	7	481.5	7.80	69.77	0.740	0.011
80	1.5	50	4	6	598.7	8.36	40.70	1.074	0.026
80	1.5	50	3	4	277.4	7.43	61.05	0.746	0.012
80	3	50	2	5	511.2	13.94	48.84	1.101	0.023
80	3	50	3	7	578.5	13.01	34.89	0.890	0.025
80	3	50	3	7.5	638.7	13.94	32.56	0.917	0.028
80	4.5	50	2	1.75	200.4	4.88	139.54	1.233	0.009
80	4.5	50	4	4	460	5.57	61.05	1.238	0.020
80	4.5	100	6	6.75	845.1	6.27	72.35	1.348	0.019

All the runs were conducted in an enclosed chamber of size 12' x 10' x 8' ventilated with a fan operated at 60 rpm: average flow rate: 3000 cfm, blasting was conducted using number #6 nozzle

Table 6 Steel Grit/Shot: Statistical Parameters

Pressure	Feed Rate	Productivity			Consumption			Emission Factor 1			Emission Factor 2		
PSI	# turns	M2/hr	Mean	SD	kg/m^2	Mean	SD	kg/m^2	Mean	SD	kg/kg	Mean	SD
120	3	9.29	10.06	1.34	48.84	45.58	5.64	1.370	1.553	0.163	0.028	0.035	0.008
120	3	9.29			48.84			1.606			0.033		
120	3	11.61			39.07			1.683			0.043		
120	4	13.01	13.14	0.40	34.89	34.13	8.74	1.253	1.396	0.140	0.036	0.043	0.011
120	4	13.59			25.04			1.400			0.056		
120	4	12.82			42.47			1.534			0.036		
120	5	12.54	12.20	0.44	54.26	44.10	11.57	2.613	2.636	0.251	0.048	0.062	0.014
120	5	12.34			31.51			2.397			0.076		
120	5	11.71			46.51			2.898			0.062		
100	3	13.94	13.63	0.54	48.84	40.93	7.16	1.023	0.993	0.065	0.021	0.025	0.005
100	3	13.94			39.07			0.918			0.024		
100	3	13.01			34.89			1.038			0.030		
100	4	16.72	16.34	0.35	32.56	34.31	7.44	1.245	1.300	0.067	0.038	0.039	0.007
100	4	16.26			27.91			1.280			0.046		
100	4	16.03			42.47			1.375			0.032		
100	5	5.85	7.39	1.35	83.72	62.28	18.77	2.496	2.509	0.226	0.030	0.043	0.013
100	5	7.96			48.84			2.741			0.056		
100	5	8.36			54.26			2.290			0.042		
80	3	7.80	7.87	0.47	69.77	57.17	14.92	0.740	0.854	0.191	0.011	0.016	0.009
80	3	8.36			40.70			1.074			0.026		
80	3	7.43			61.05			0.746			0.012		
80	4	13.94	13.63	0.54	48.84	38.76	8.80	1.101	0.969	0.115	0.023	0.025	0.003
80	4	13.01			34.89			0.890			0.025		
80	4	13.94			32.56			0.917			0.028		
80	5	4.88	5.57	0.70	139.54	90.98	42.43	1.233	1.273	0.065	0.009	0.016	0.006
80	5	5.57			61.05			1.238			0.020		
80	5	6.27			72.35			1.348			0.019		

All the runs were conducted in an enclosed chamber of size 12' x 10' x 8' ventilated with a fan operated at 60 rpm: average flow rate: 3000 cfm, blasting was conducted using number #6 nozzle

Since productivity, consumption and emissions (concentrations as well as compositions) are simultaneously influenced by blast pressure and feed rate, it was first necessary to study the effects of pressure at various feed rates and feed rates at various pressures. From the field data, two-dimensional plots were generated to understand the effect of (a) pressure at various feed rate conditions tested and (b) feed rate at various blast pressure settings. Subsequently, three-dimensional plots to observe and understand the simultaneous influences were developed using multiple regression techniques. This chapter presents the obtained plots along with explanations of trends in observed behavior.

5.1 Productivity Variation with Abrasive Feed Rate

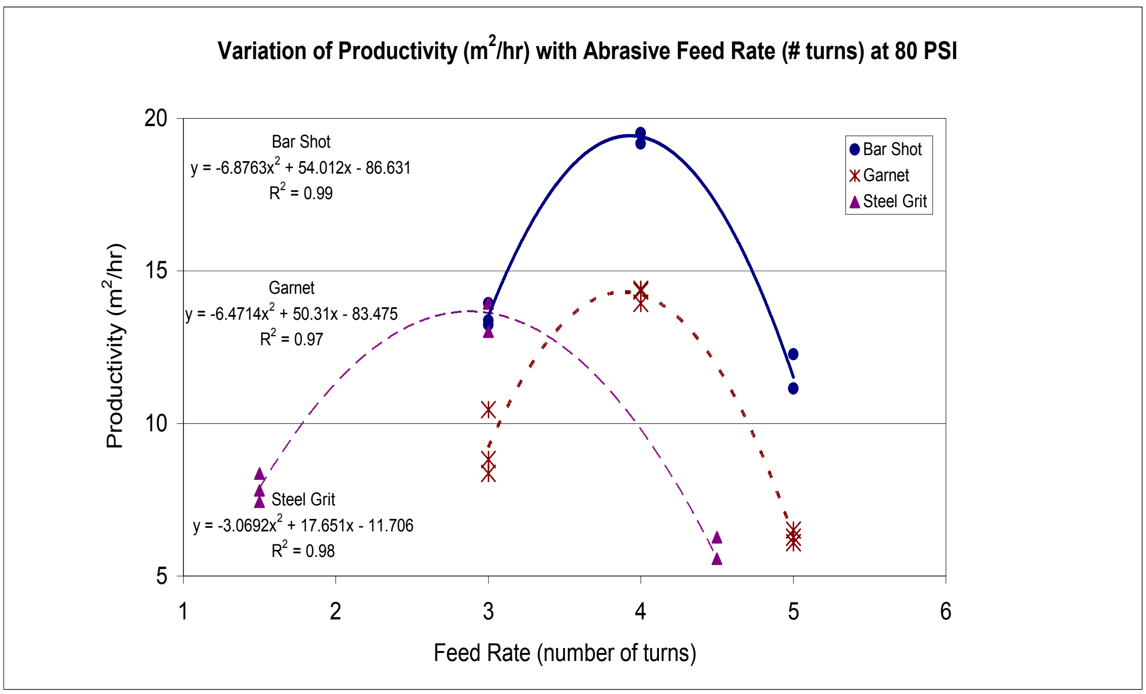


Figure 12 Variation of Productivity with Abrasive Feed rate (# turns) at 80 PSI

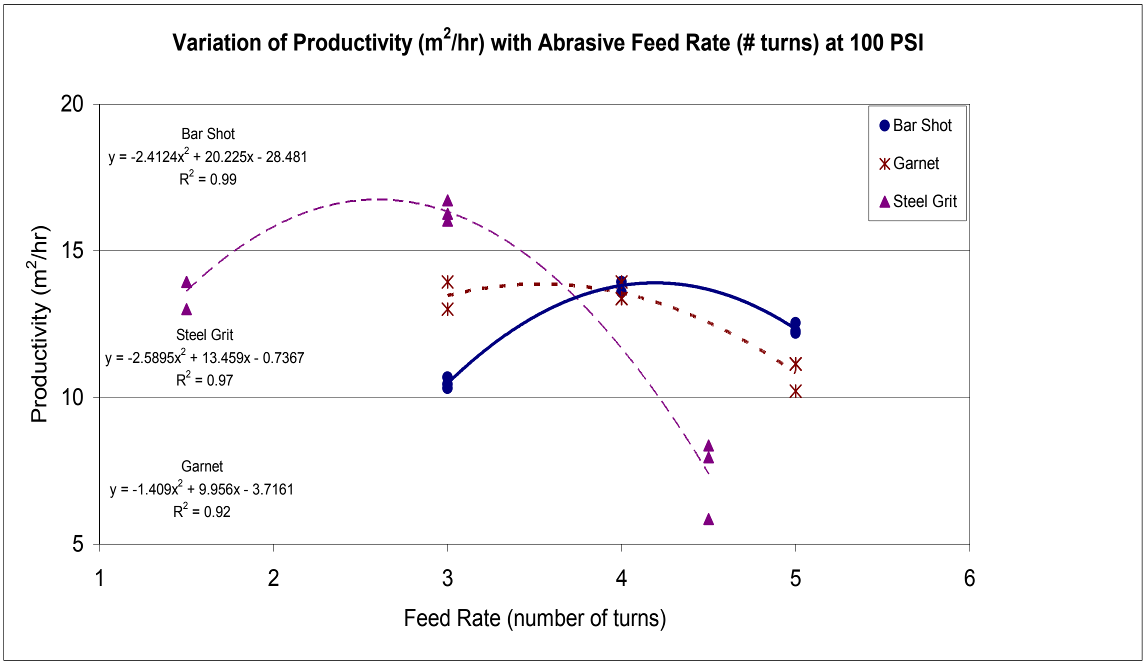


Figure 13 Variation of Productivity with Abrasive Feed rate (# turns) at 100 PSI

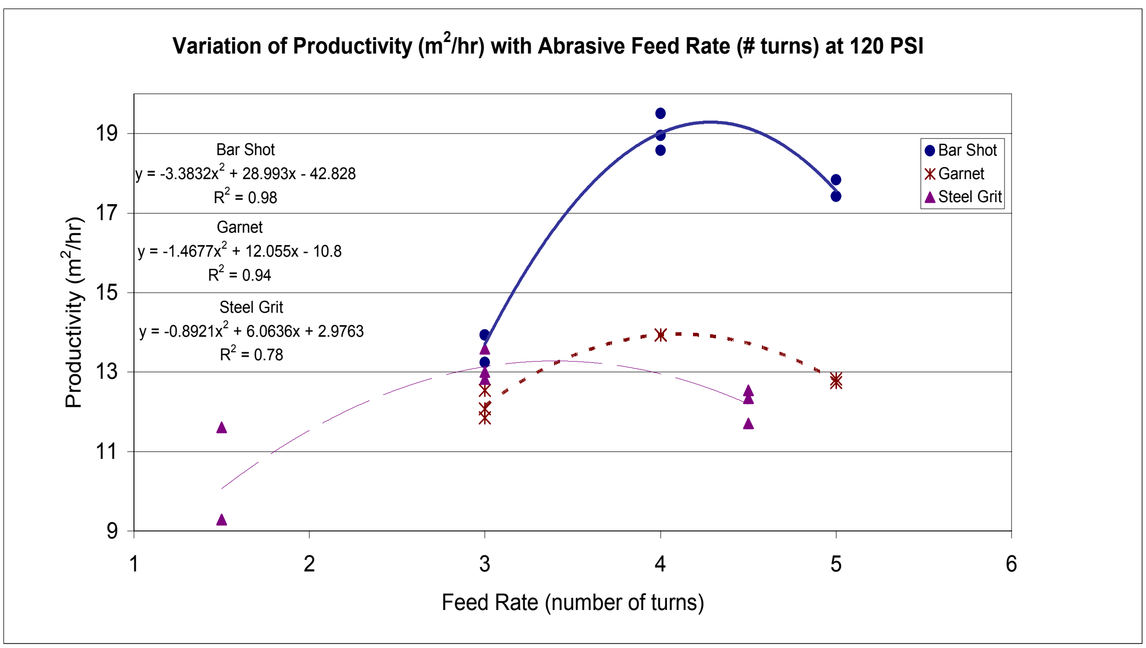


Figure 14 Variation of Productivity with Abrasive Feed rate (# turns) at 120 PSI

Garnet:

Productivity variation with feed rate (number of turns) at 80, 100 and 120 PSI are shown in Figures 12, 13 and 14 respectively. At all the three tested pressures, a “bell-shaped” curve was obtained for productivity. This implies that at a given pressure, productivity increases with feed rate till a threshold feed rate and decreases henceforth. Productivity is directly proportional to the number of particles hitting the metal surface to be blasted. The momentum of the particles is a function of the blast pressure, nozzle size and abrasive feed rate. As the mass flow rate (governed by feed rate setting) increases, the momentum of the particles increase resulting in an increase in number of particles reaching the surface. This corresponds to a higher particle flux (number of particles per unit area of the plate) which causes an increase in the area cleaned till a threshold feed rate. At feed rates higher than this critical feed rate, the particle rebound rate increases gradually. This results in a reduction in number of particles actually reaching the metal surface. Though both material feed rate and particle velocity continue to increase as expected, the actual number of particles involved in blasting the metal plate decreases after this critical feed rate setting (four turns). This explains the "bell-shaped" curve obtained at all the three pressure settings.

Steel Grit/Shot: It can be seen from Figures 12, 13 and 14 that at blast pressures of 80, 100 and 120 PSI, productivity increases with feed rate till three turns and decreases hence forth. A "bell-shaped" pattern was observed with high correlation coefficients in all three cases. As mentioned earlier, the cleaning rate is influenced by the momentum of the abrasive particles which is a function of both the mass and particle velocity. The former is influenced by the material feed rate and the latter by blast pressure. At higher pressures and feed rate settings, the particle rebound rate is higher resulting in a lesser mass flux of particles reaching the metal surface. Also, at higher pressure and feed rate conditions, back pressure on the abrasive hose increases, causing discomfort to the blaster resulting in loss of productivity. Hence, there is a threshold feed rate till which productivity increases and decreases hence forth. This explains the bell shaped curve obtained for productivity variation with feed rate.

Bar Shot: For all the blast pressures tested, a bell shaped curve was observed for productivity vs. feed rate. This indicates that productivity increases from a feed rate of three turns until a feed rate of four, and then decreases from there on. The reasons for the same have been explained before. The correlation coefficients are very high in all these cases indicating a strong relationship.

5.2 Productivity Variation with Blast Pressure

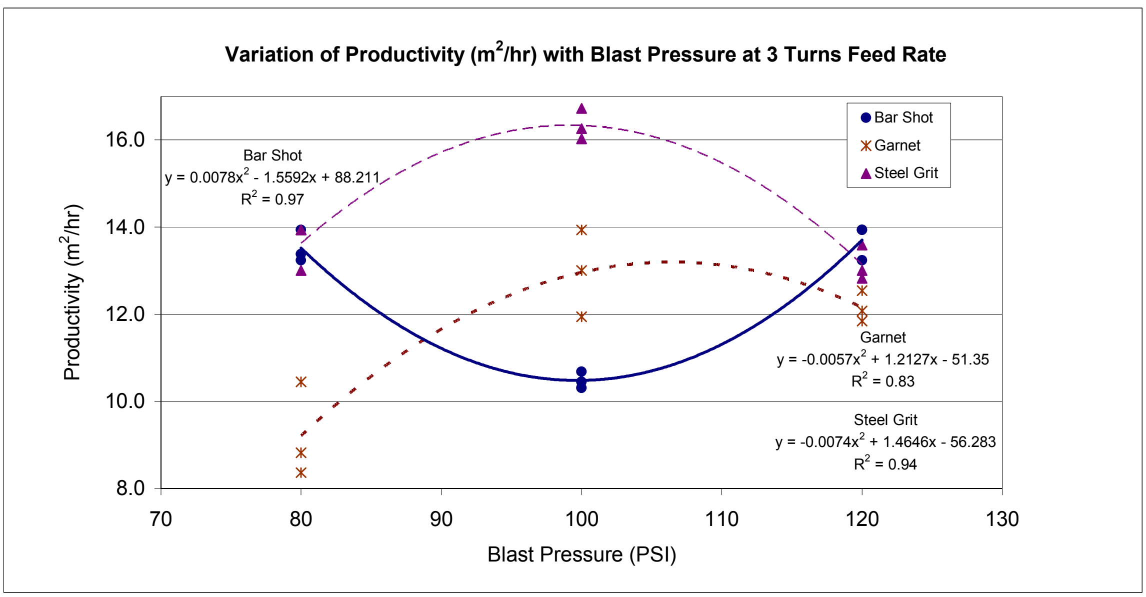


Figure 15 Variation of Productivity with Blast Pressure at 3 turns Feed Rate

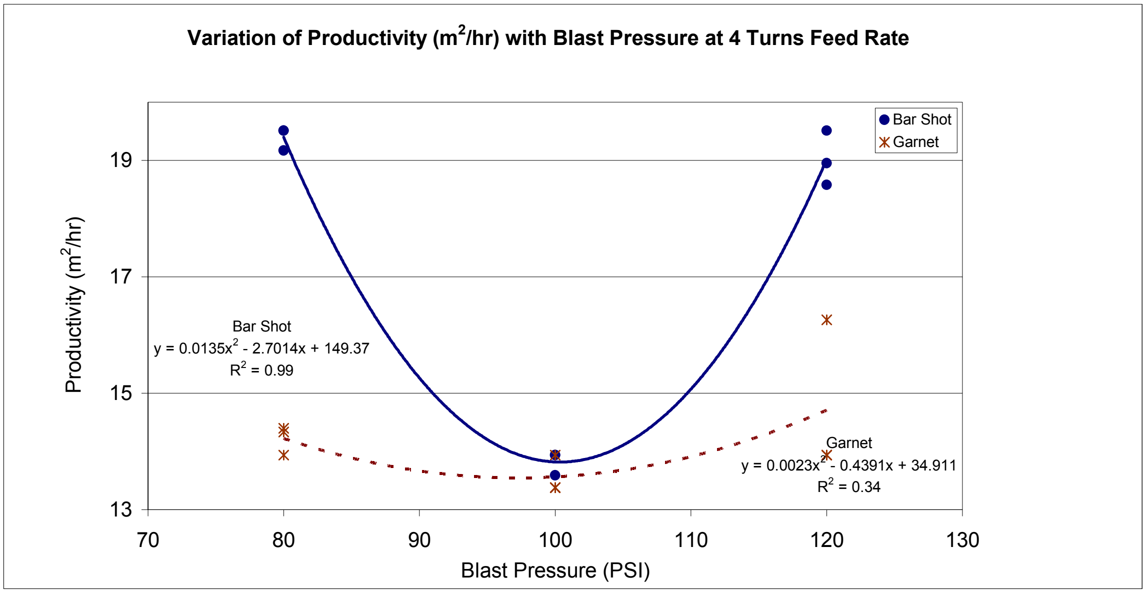


Figure 16 Variation of Productivity with Blast Pressure at 4 turns Feed Rate

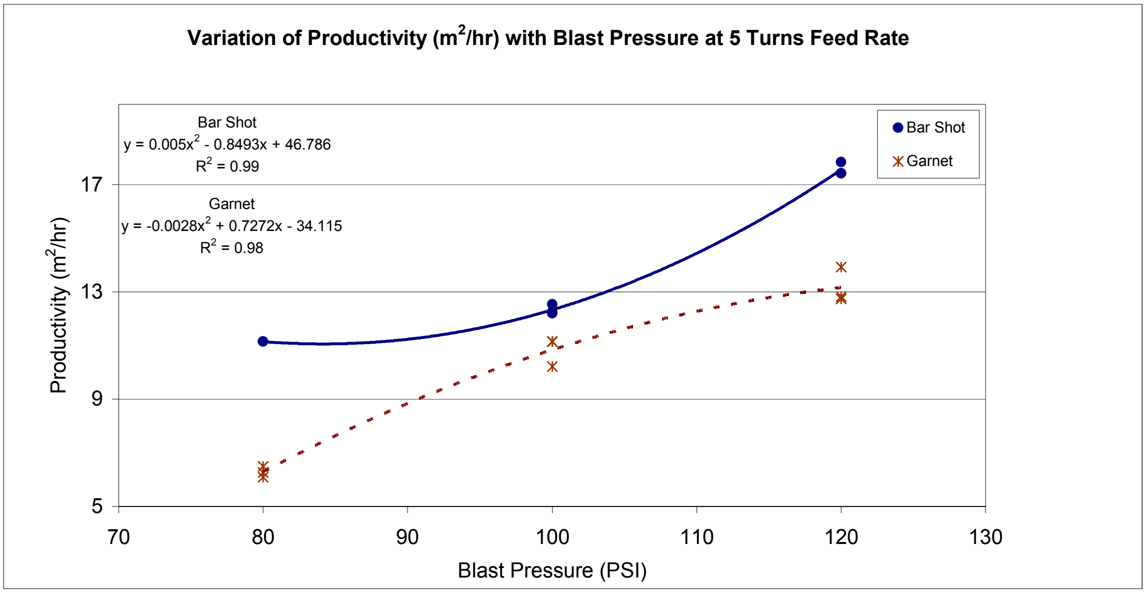


Figure 17 Variation of Productivity with Blast Pressure at 5 turns Feed Rate

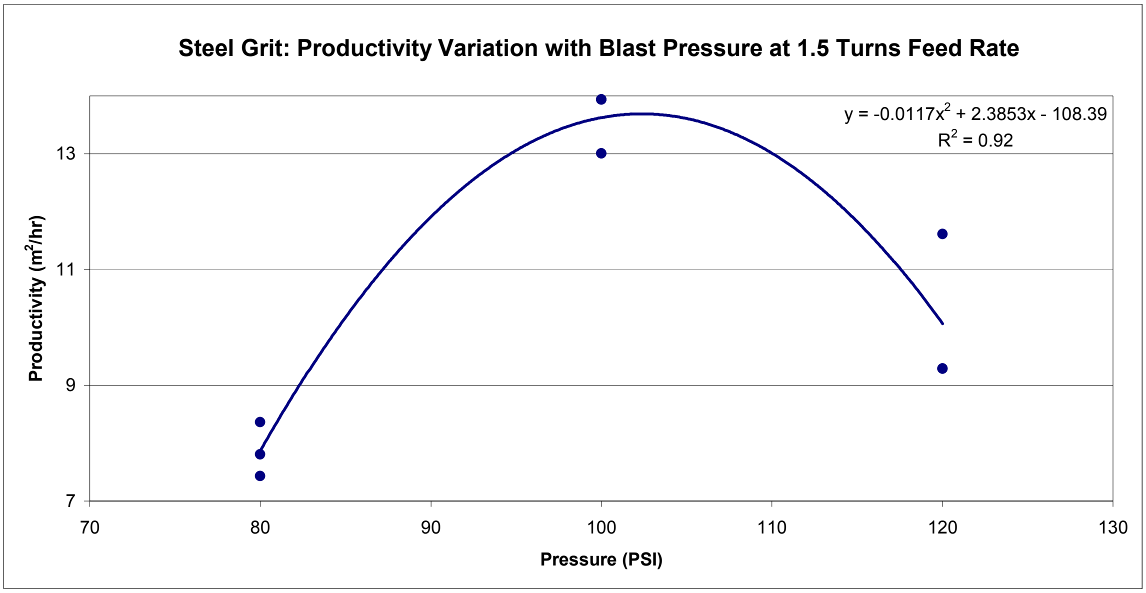


Figure 18 Variation of Productivity with Blast Pressure at 1.5 turns Feed Rate

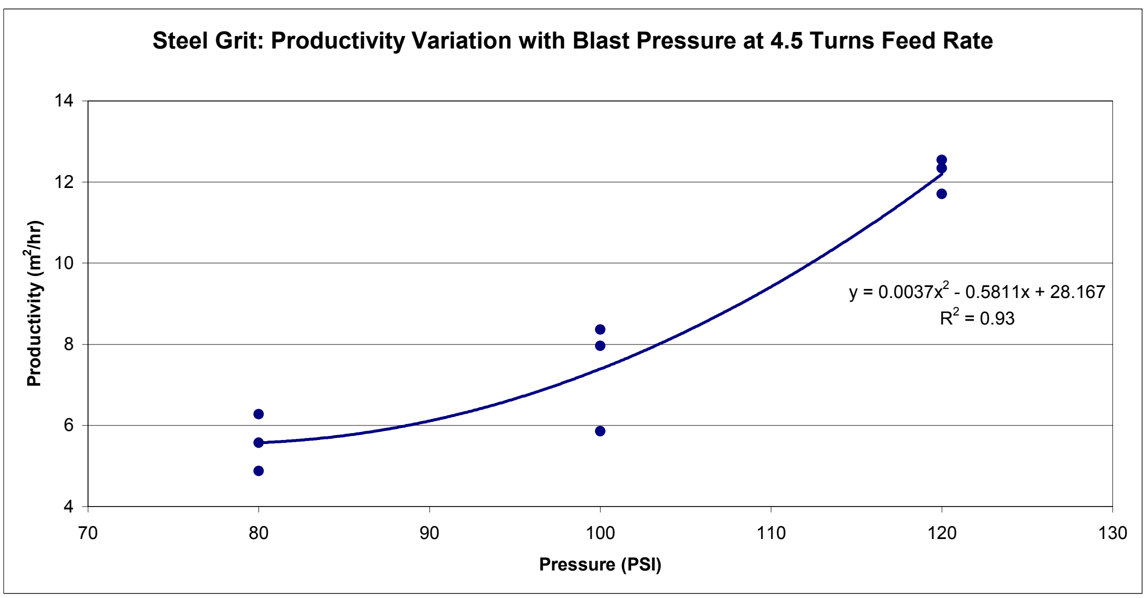


Figure 19 Variation of Productivity with Blast Pressure at 4.5 turns Feed Rate

Garnet: At three turns feed rate condition rusted panels and painted panels showed varying trends for productivity variation with blast pressure. This can be seen from Figure 15. Productivity increased from 80 PSI till 100 PSI and did not vary significantly from 100 PSI to

120 PSI. Blast pressures more than 100 PSI might lead to greater particle rebound rates, lower visibility inside the shed, higher back pressure on the hose making it difficult and unsafe for the blaster. All these factors result in lowering the productivity over a blast pressure of 100 PSI. However, at a feed rate setting of five turns (Figure 17), productivity increased with blast pressure.

Steel grit/shot: From Figures 15 and 18, it can be observed that at 1.5 and 3 turns feed rate, a "bell shaped" pattern is observed for productivity variation with blast pressure. The reasons for the bell shaped pattern have been described in an earlier section. At a feed rate corresponding to 4.5 turns productivity did not vary much from 80 to 100 PSI but increased significantly from 100 PSI to 120 PSI.

Barshot: We find that productivity decreases with pressure till 100 PSI and then increases for a specific feed rate, but this trend is not uniform. The correlations obtained are strong and the equations can be applied to predict productivities at any intermediate pressures. At a feed rate of 5 turns, productivity increased with pressure.

5.3 Consumption Variation with Abrasive Feed Rate

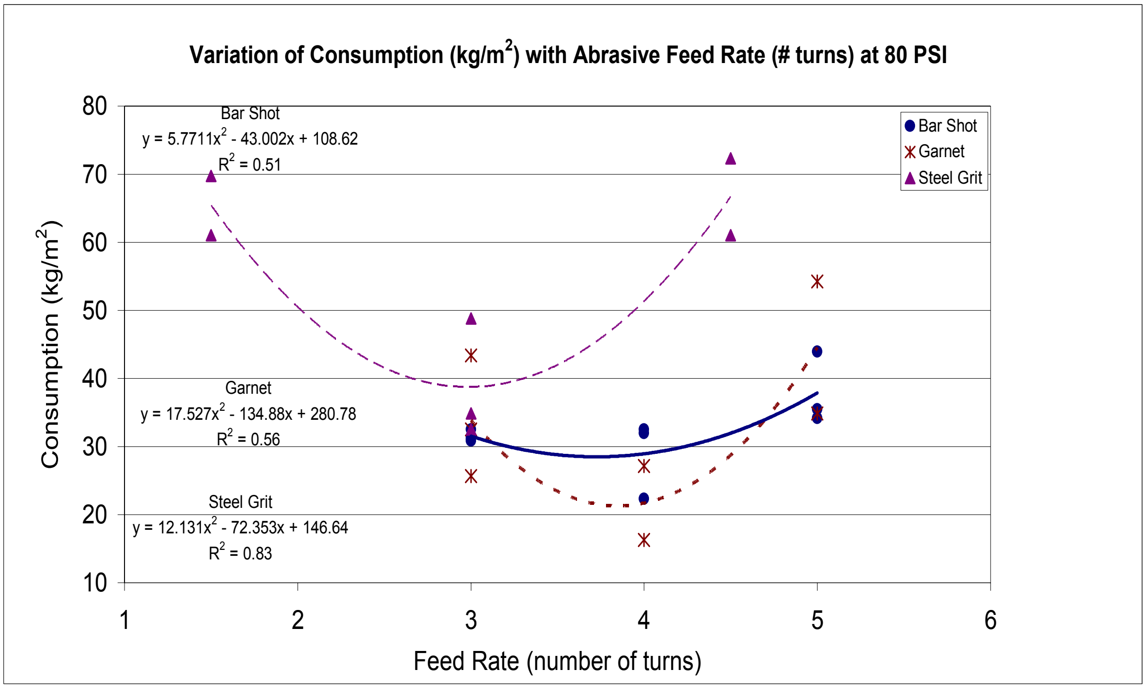


Figure 20 Variation of Consumption with Abrasive Feed rate (# turns) at 80 PSI

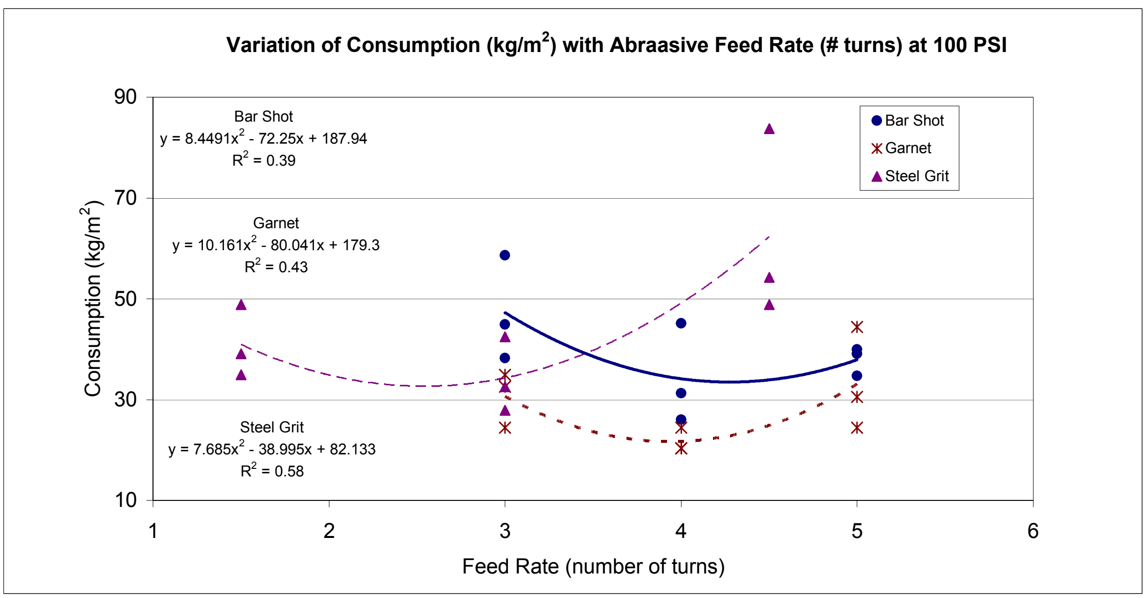


Figure 21 Variation of Consumption with Abrasive Feed rate (# turns) at 100 PSI

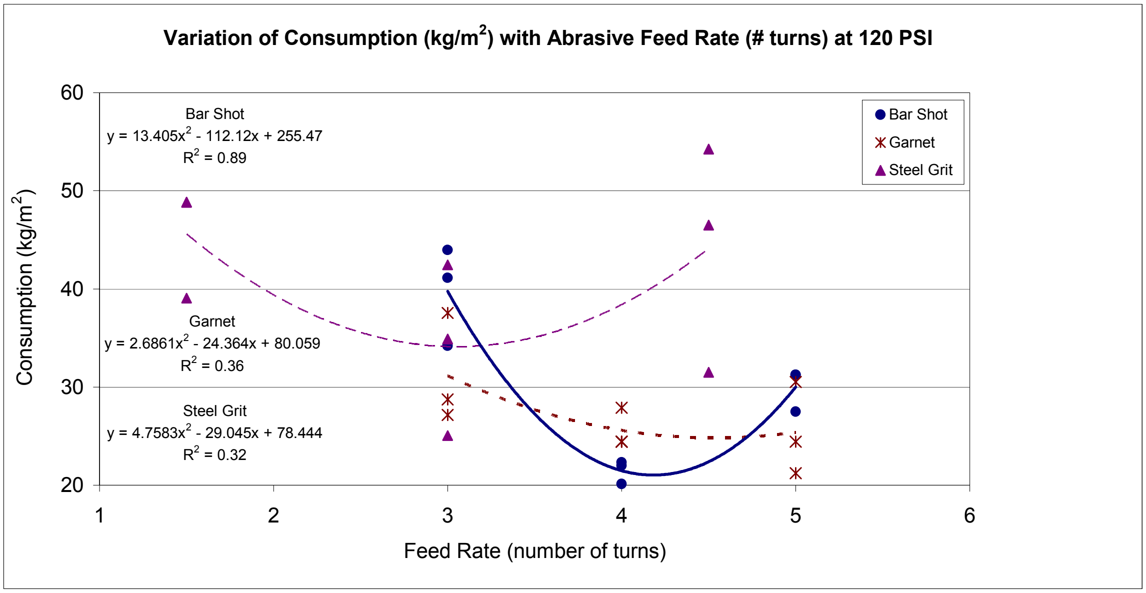


Figure 22 Variation of Consumption with Abrasive Feed rate (# turns) at 120 PSI

Garnet: Figures 19 - 21 show the variation of consumption with feed rate expressed in number of turns. It can be observed in most of the cases that consumption variation follows an inverse pattern as that of productivity variation. At 80 PSI, there is a significant drop in consumption from three turns till four turns feed rate. In case of painted panels, there is an increase in consumption from four to five turns. At 100 and 120 PSI, inverted bell shape patterns were observed showing that there is a drop in consumption at a feed rate corresponding to four turns.

Steel grit/shot: Trends in consumption variation with feed rate at the three tested pressures for steel grit are shown in Figures 19-21. An inverse bell shaped curve was observed in most of the cases. This can be explained as follows. As explained in the previous section, productivity increases till a threshold feed rate and then decreases. The amount of abrasive required to clean a given area decreases until the threshold feed rate since a higher cleaning rate is achieved owing to increasing particle momentum and blasting efficiency. After the threshold feed rate to clean a given area, more material is consumed for the reasons listed in the productivity variation discussion.

Barshot: The consumption plots for bar shot show inverted bell shaped curves for the reasons discussed earlier.

5.4 Consumption Variation with Blast Pressure

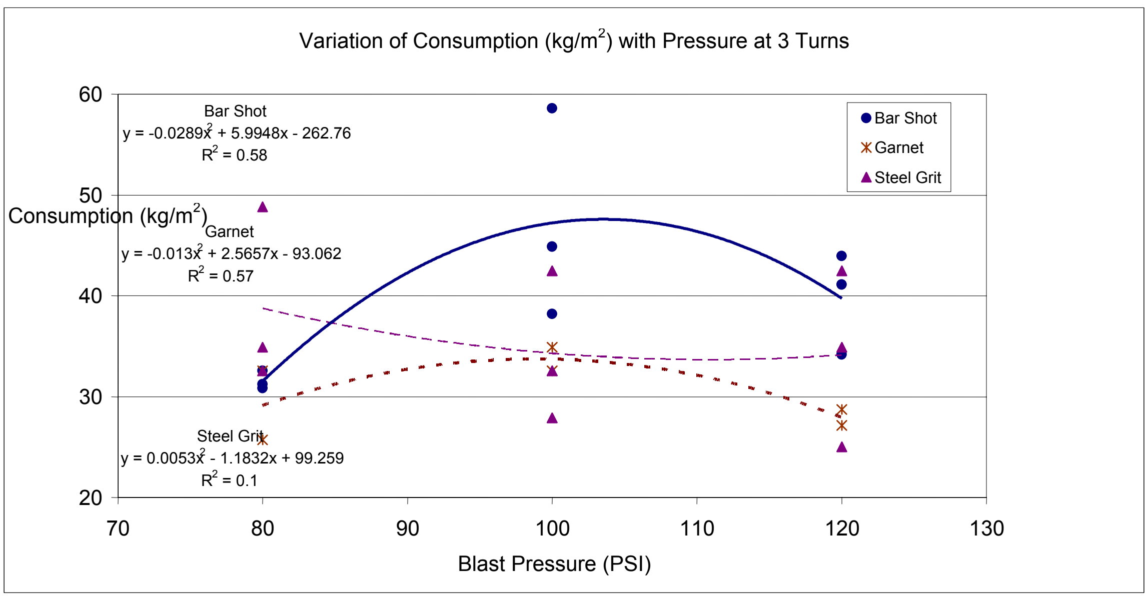


Figure 23 Variation of Consumption with Blast Pressure at 3 turns Feed Rate

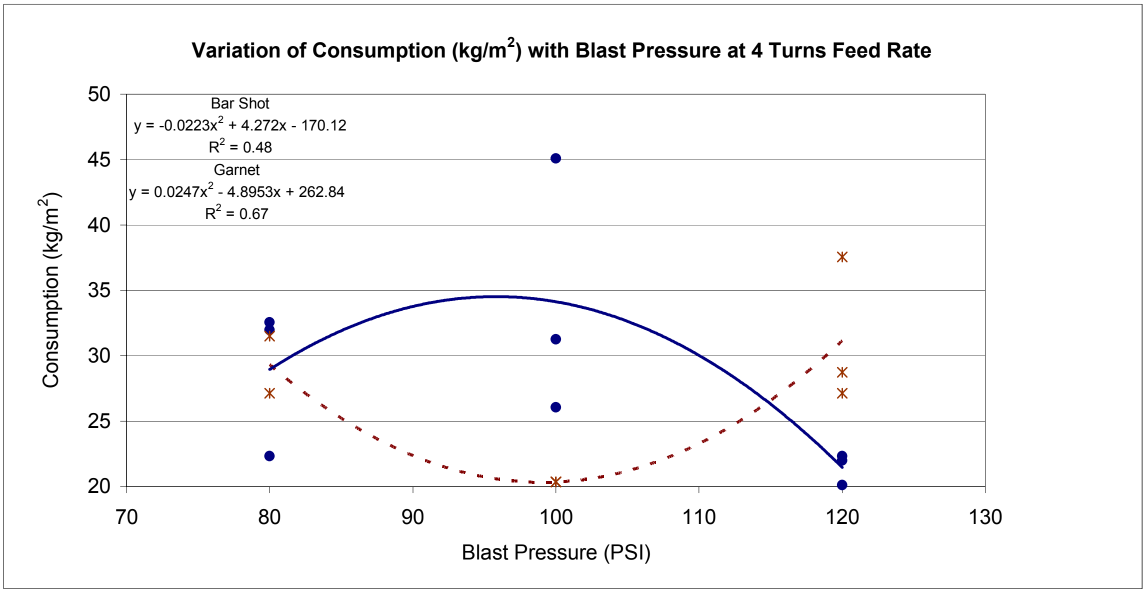


Figure 24 Variation of Consumption with Blast Pressure at 4 turns Feed Rate

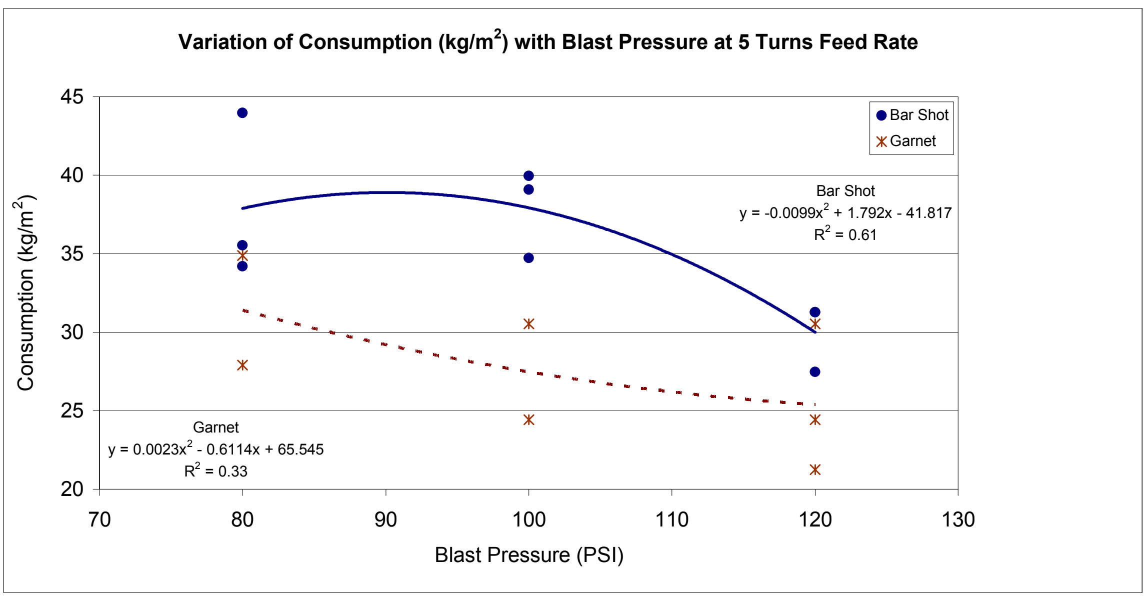


Figure 25 Variation of Consumption with Blast Pressure at 5 turns Feed Rate

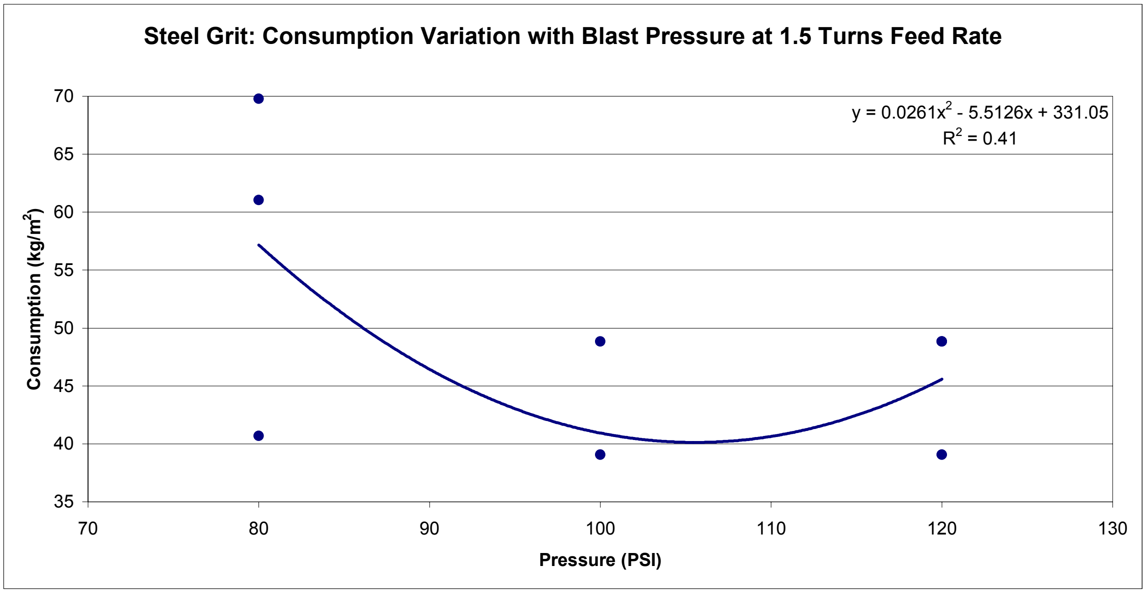


Figure 26 Variation of Consumption with Blast Pressure at 1.5 turns Feed Rate

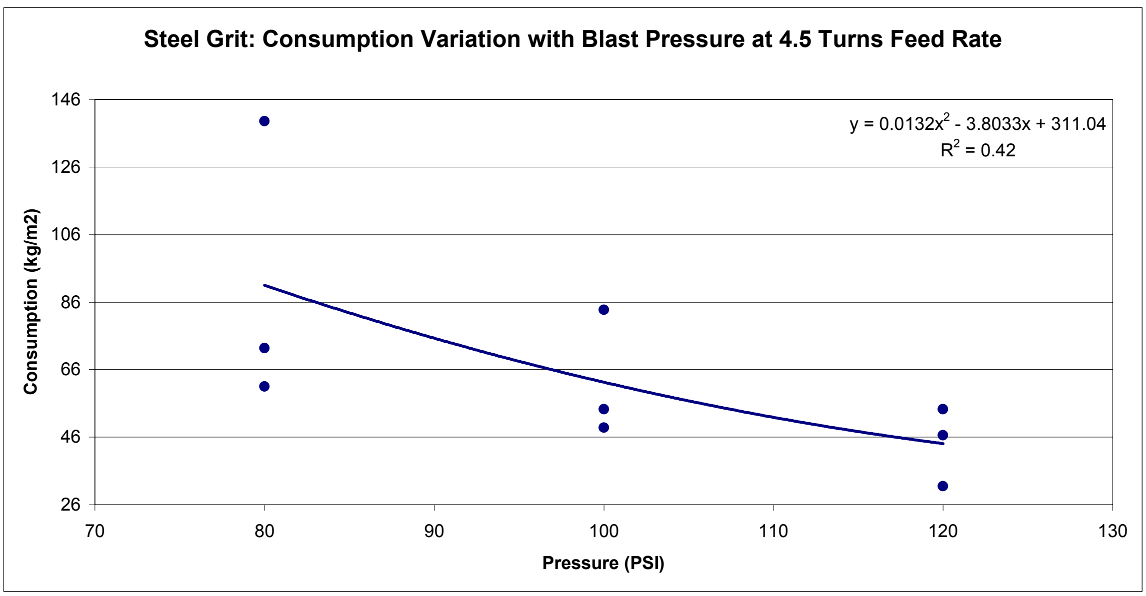


Figure 27 Variation of Consumption with Blast Pressure at 4.5 turns Feed Rate

Garnet: At three turns feed rate condition, consumption decreased from 80 to 100 PSI and then increased until 120 PSI. This can be attributed to the lower material usage rate at higher pressure conditions for the same area cleaned. At four turns feed rate condition also, (Figure 23), consumption decreased until 100 PSI and then increased until 120 PSI. At five turns feed rate condition however, consumption decreased with pressure (Figure 24).

Barshot: Bell shaped curves were obtained for consumption variation with blast pressure at the three tested feed rates, the reasons for which have been discussed earlier.

Steel grit/shot: At 3 turns feed rate condition, consumption remained almost constant at all pressures. This might mean that at three turns condition, pressure does not have an effect on material consumption. However at 1.5 as well as 4.5 turns, consumption decreased slightly with blast pressure. But, there seems to be some other factor dominating consumption since correlation coefficients obtained in all three cases are low.

5.5 TPM Emission Factors Variation with Abrasive Feed Rate

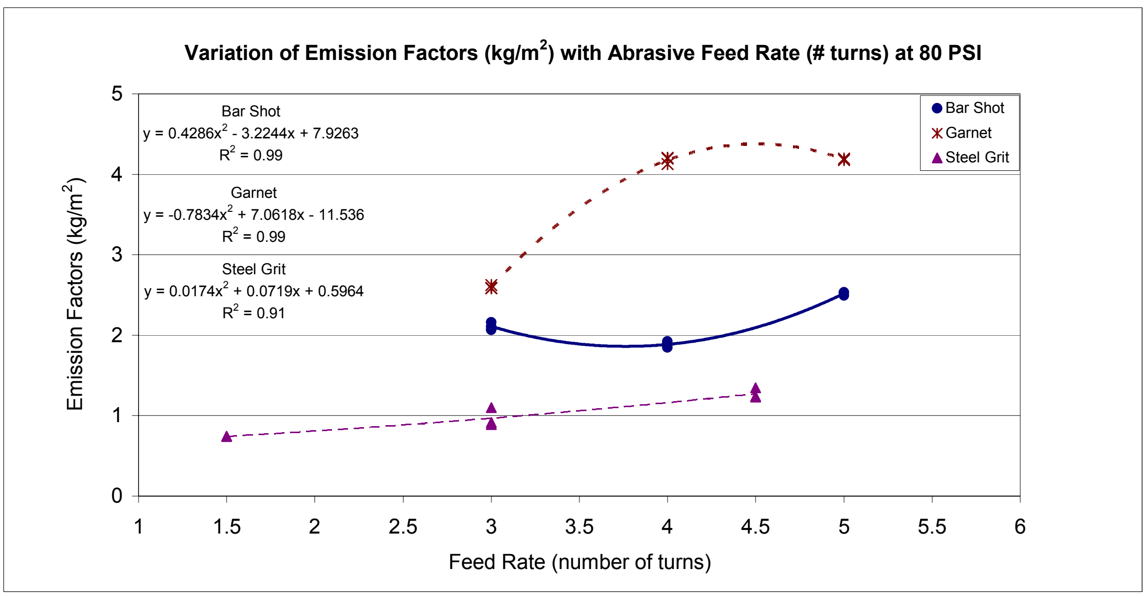


Figure 28 Variation of Emission Factors (kg/m^2) with Abrasive Feed Rate at 80 PSI

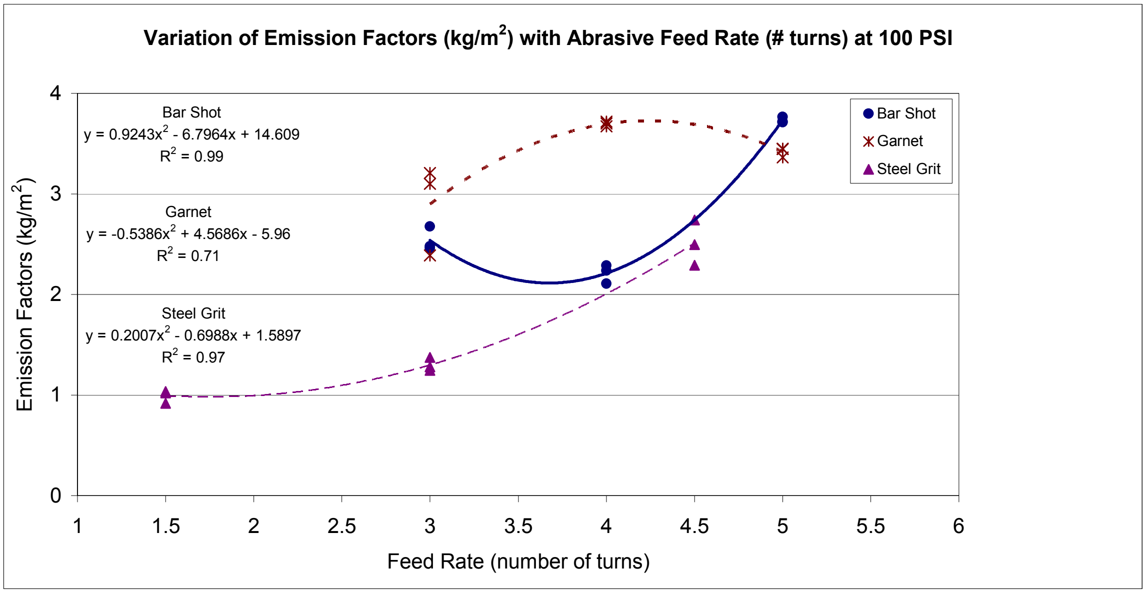


Figure 29 Variation of Emission Factors (kg/m^2) with Abrasive Feed Rate at 100 PSI

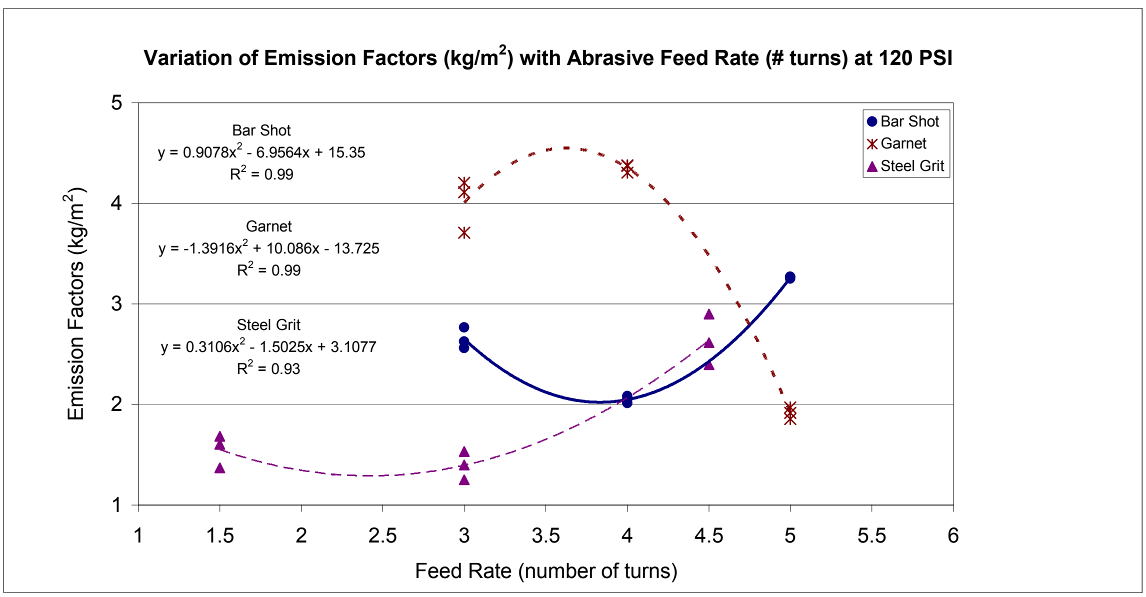


Figure 30 Variation of Emission Factors (kg/m^2) with Abrasive Feed Rate at 120 PSI

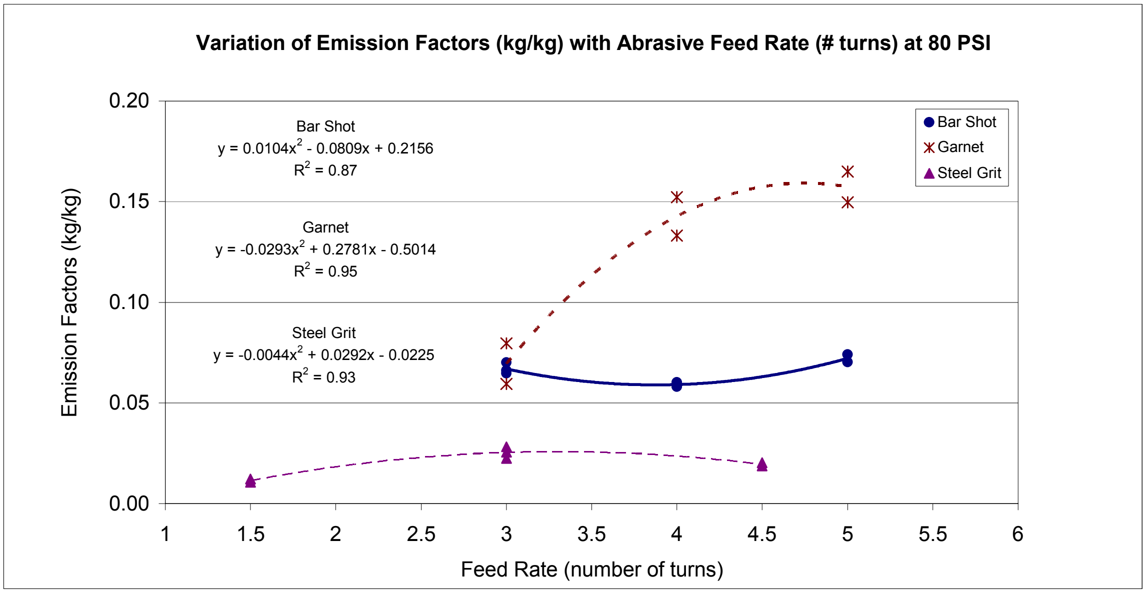


Figure 31 Variation of Emission Factors (kg/kg) with Abrasive Feed Rate at 80 PSI

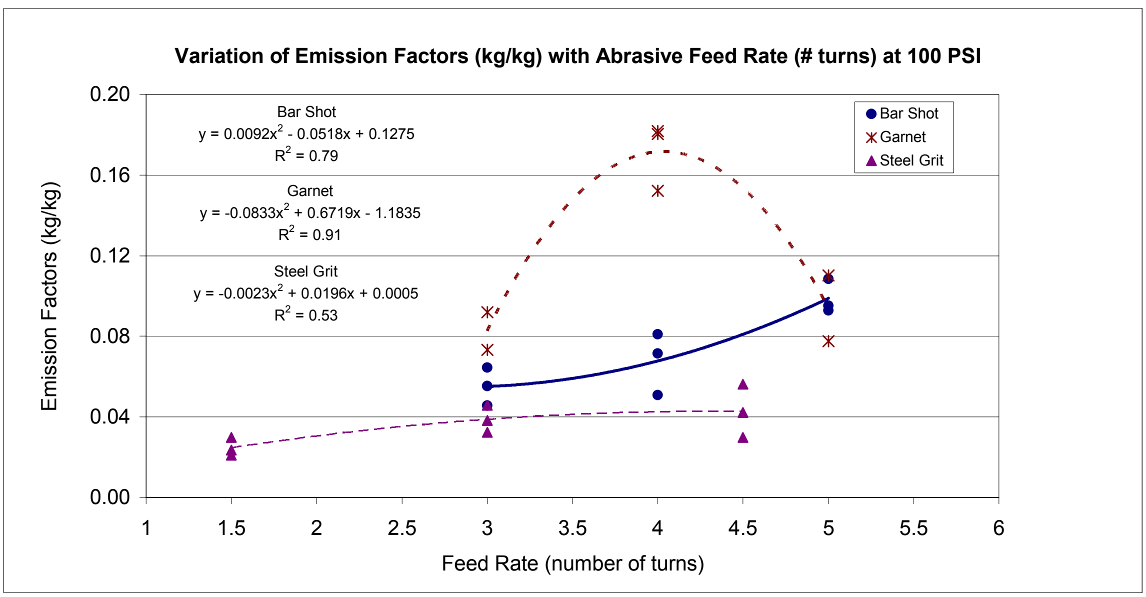


Figure 32 Variation of Emission Factors (kg/kg) with Abrasive Feed Rate at 100 PSI

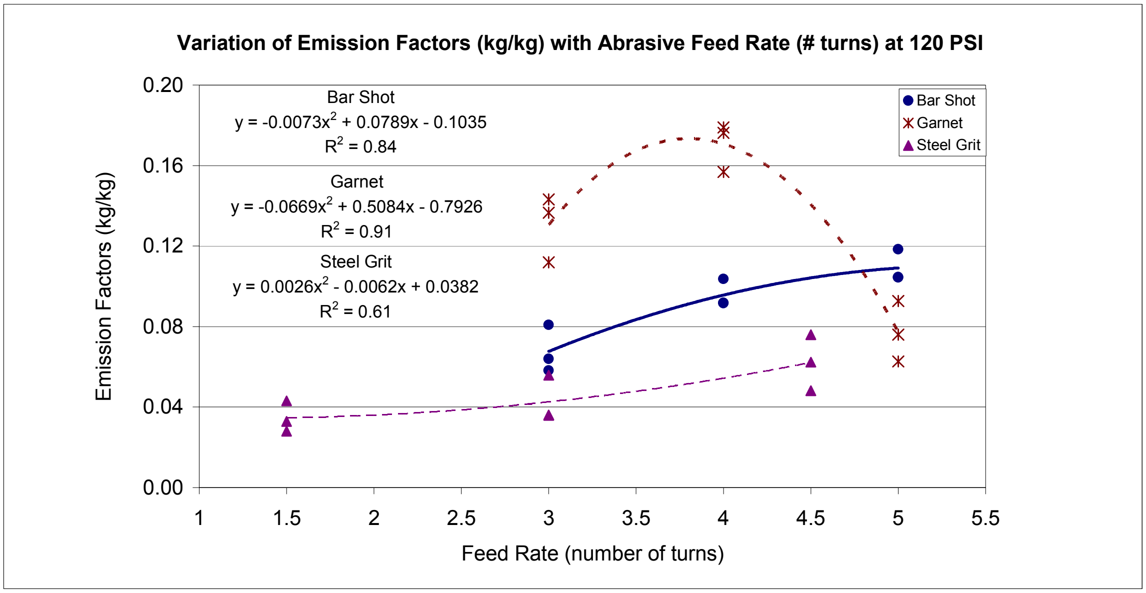


Figure 33 Variation of Emission Factors (kg/kg) with Abrasive Feed Rate at 120 PSI

Garnet: At 80 PSI, emission factors (kg/m^2) increase with feed rate from three to four turns. However, there is not a marked variation in emission factors from four to five turns feed rate setting. The same trend was observed at 100 PSI too, but the correlation was not as strong as at 80 PSI. Uncontrolled TPM emission factors increased three turns to four turns feed rate setting. At 120 PSI however, a contrary trend was observed (Figure 29). Emission factors (kg/m^2) were in the same range from three to four turns but decreased significantly from four to five turns (r^2 = 0.99). Mass based emission factor (kg/kg) variation with feed rate at the three tested pressures are shown in Figures 30, 31 and 32 respectively. At 100 and 120 PSI, a bell shaped pattern was observed with high correlations coefficients (r^2 = 0.91). This means that feed rate setting of four turns is likely to be the critical setting after which emission factors tend to decrease with feed rate. At 80 PSI on the other hand, emission factors increased with feed rate (r^2 = 0.95). It is important to note the increase in emission factors (kg/kg) from four to five turns, which was much lesser than that from three to four).

Steel grit/shot: Figures 30-32 show the variation of emission factors with feed rate (# turns) at the three tested blast pressures. From the figures, it can be seen that at blast pressures of 80, 100 and 120 PSI, emission factors (kg/m^2) increase with feed rate for painted panels. A bell-shaped pattern was observed with a high r^2 (0.93) was observed for emission factors (kg/kg) at 80 PSI. These emission factors increased from 1.5 to three turns and then decreased until 4.5 turns Schmidt valve setting. At 100 PSI and 120 PSI, emission f actors (kg/kg) increased with feed rate but this correlation was not so strong as compared to similar variations of emission factors expressed in kg/m^2.

Barshot: Figures 27-32 show the variation of emission factors (in kg/m^2 as well as kg/kg) with respect to feed rate (number of turns) at the tested blast pressures. It can be observed from Figure 2 that at all the three tested pressures, emission factors expressed in kg/m^2 decreased with feed rate till four turns setting of the Schmidt valve and then increased. Emission factors expressed in kg/kg increased with feed rate at all three tested conditions.

5.6 TPM Emission Factors Variation with Blast Pressure

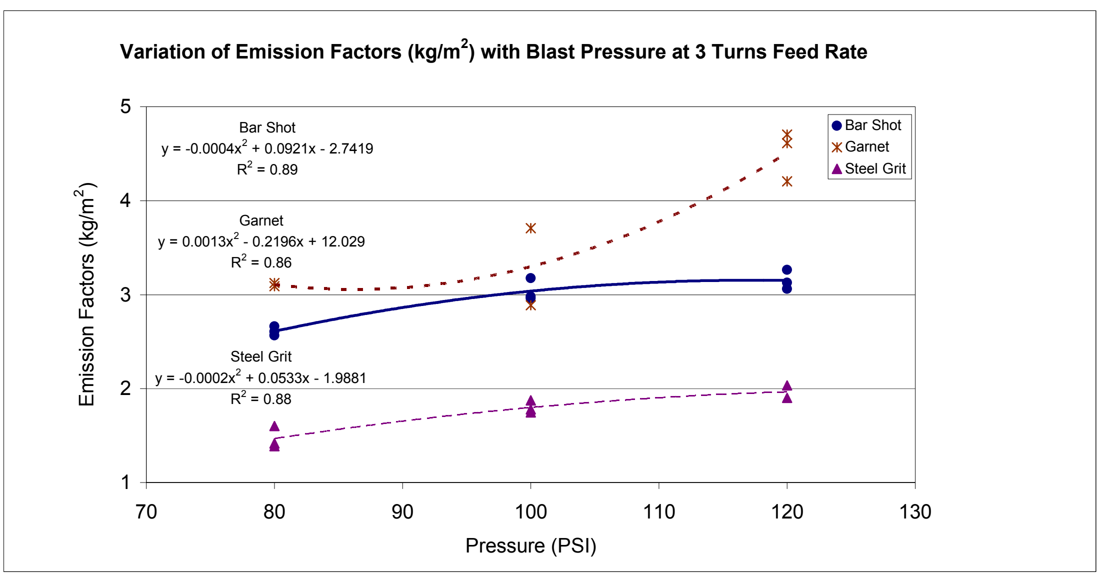


Figure 34 Variation of Emission Factors (kg/m^2) with Blast Pressure at 3 turns Feed Rate

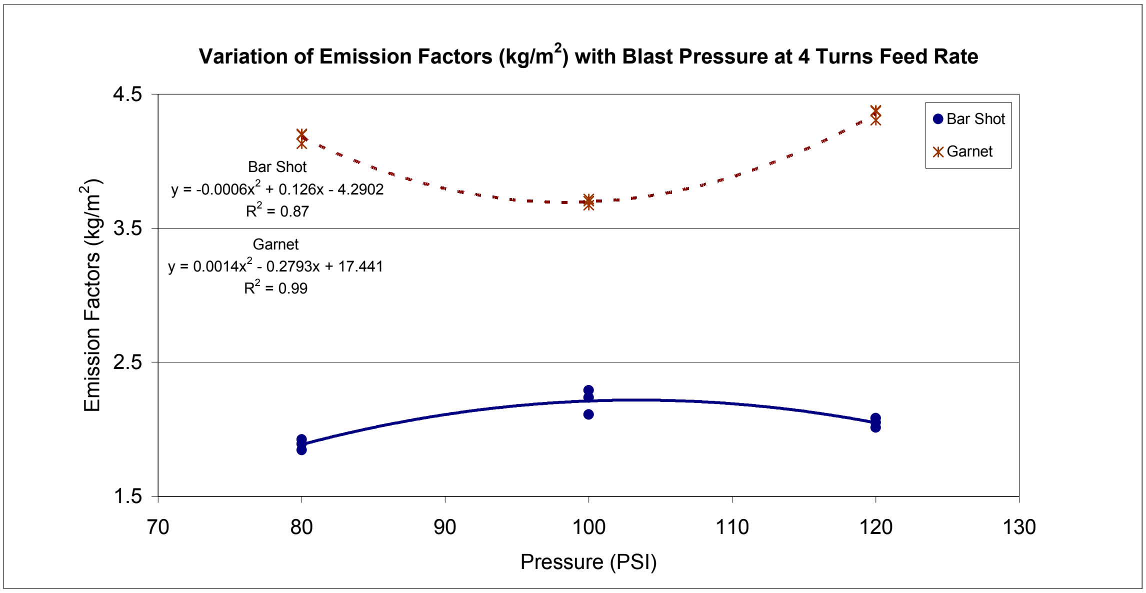


Figure 35 Variation of Emission Factors (kg/m^2) with Blast Pressure at 4 turns Feed Rate

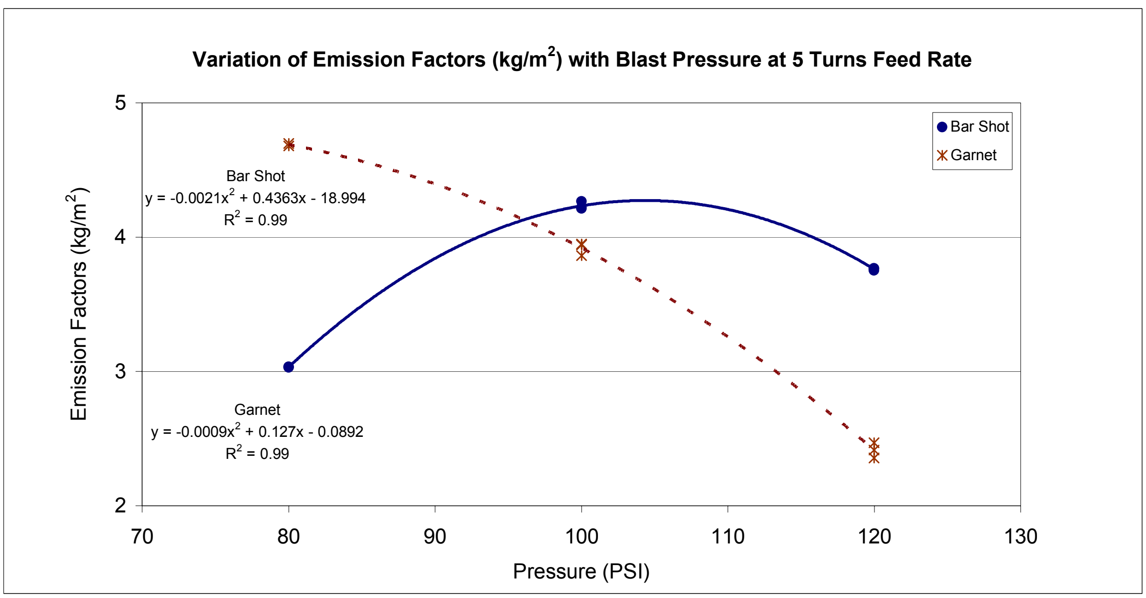


Figure 36 Variation of Emission Factors (kg/m^2) with Blast Pressure at 5 turns Feed Rate

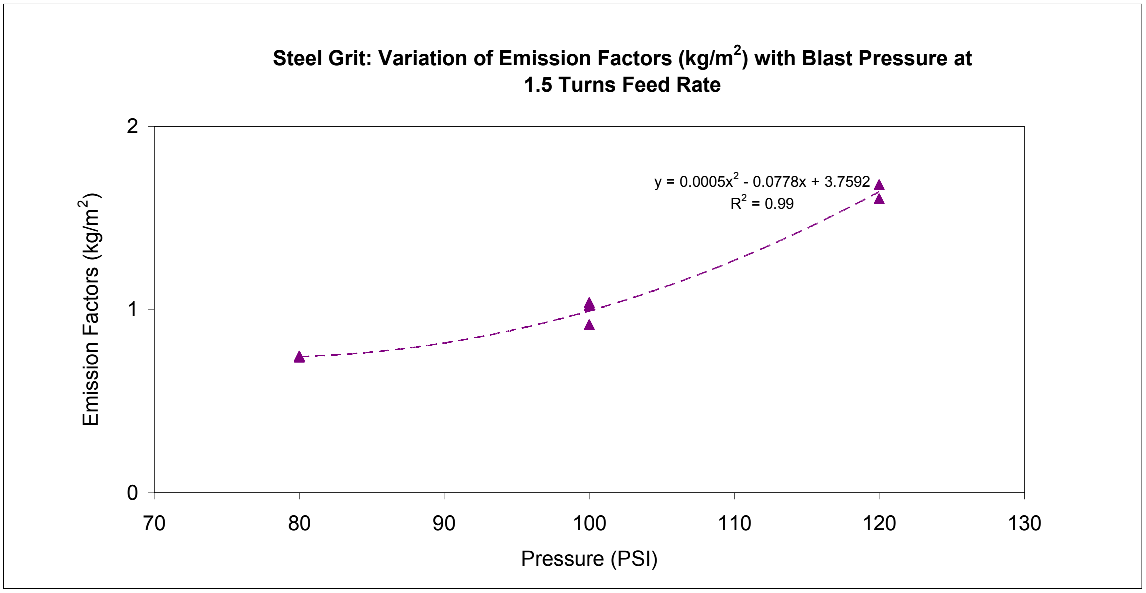


Figure 37 Variation of Emission Factors (kg/m^2) with Blast Pressure at 1.5 turns Feed Rate

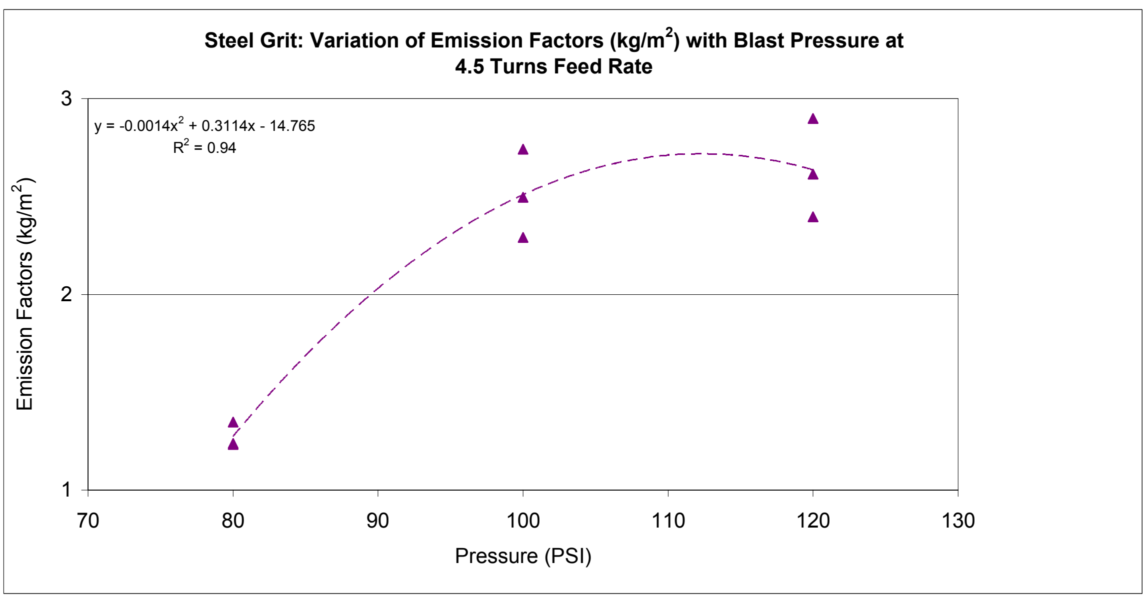


Figure 38 Variation of Emission Factors (kg/m^2) with Blast Pressure at 4.5 turns Feed Rate

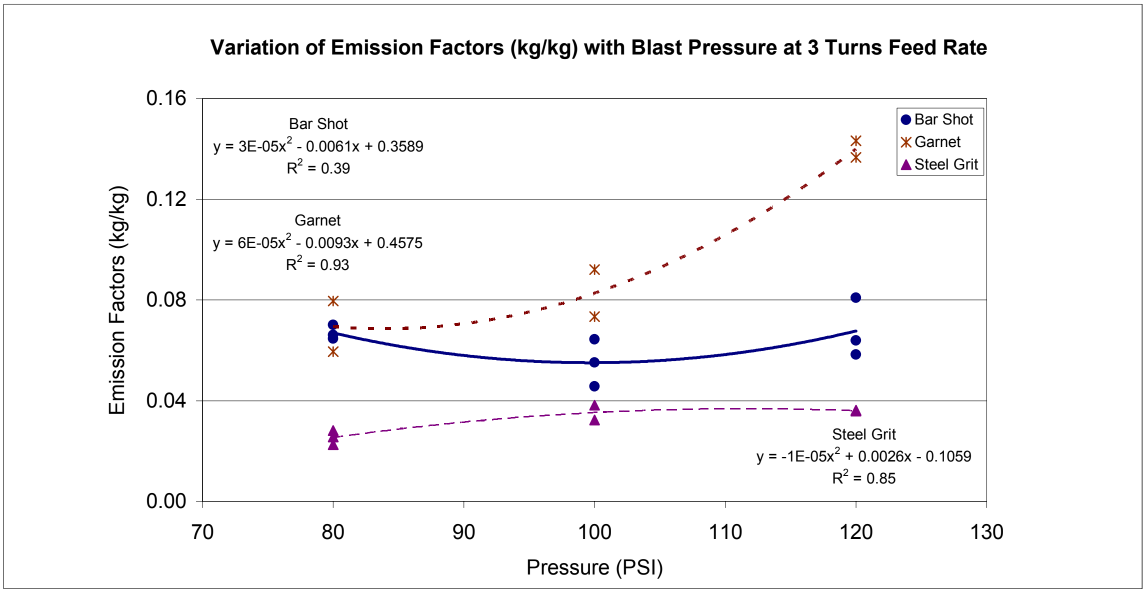


Figure 39 Variation of Emission Factors (kg/kg) with Blast Pressure at 3 turns Feed Rate

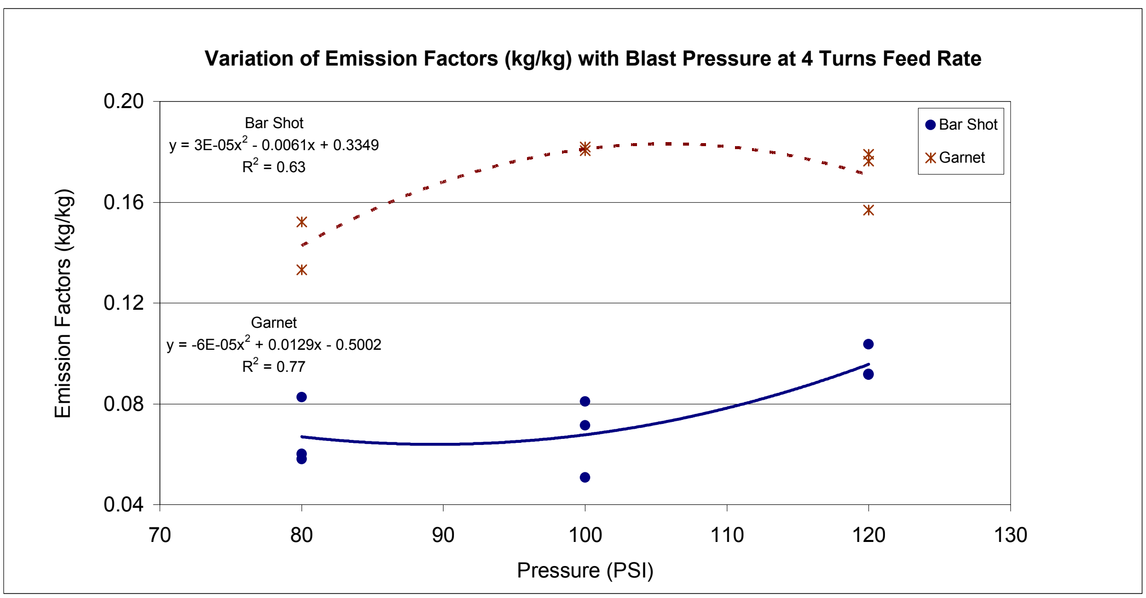


Figure 40 Variation of Emission Factors (kg/kg) with Blast Pressure at 4 turns Feed Rate

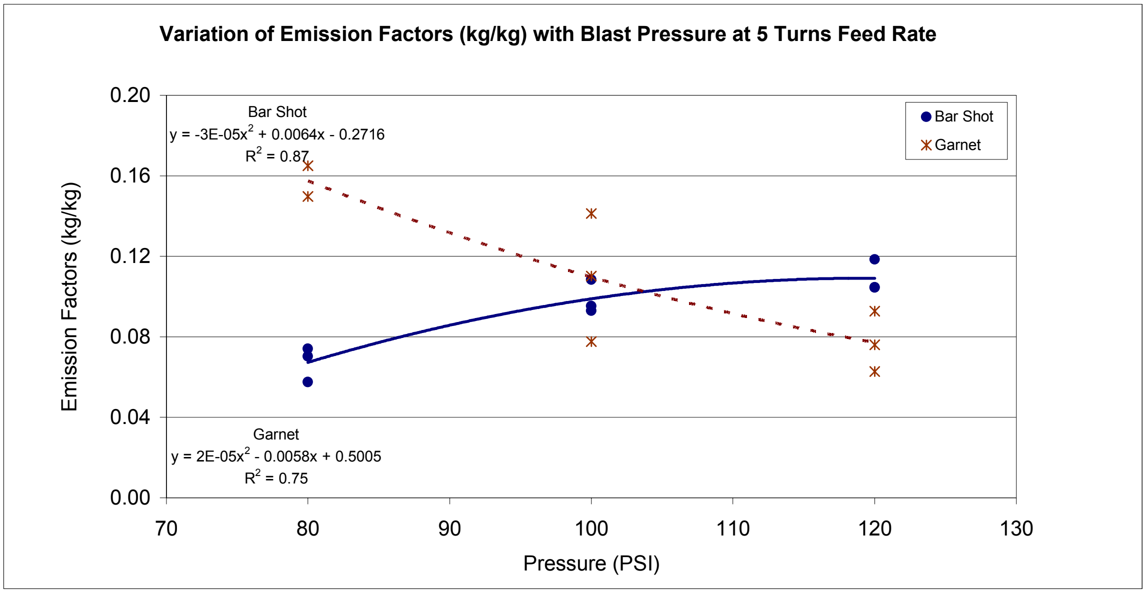


Figure 41 Variation of Emission Factors (kg/kg) with Blast Pressure at 5 turns Feed Rate

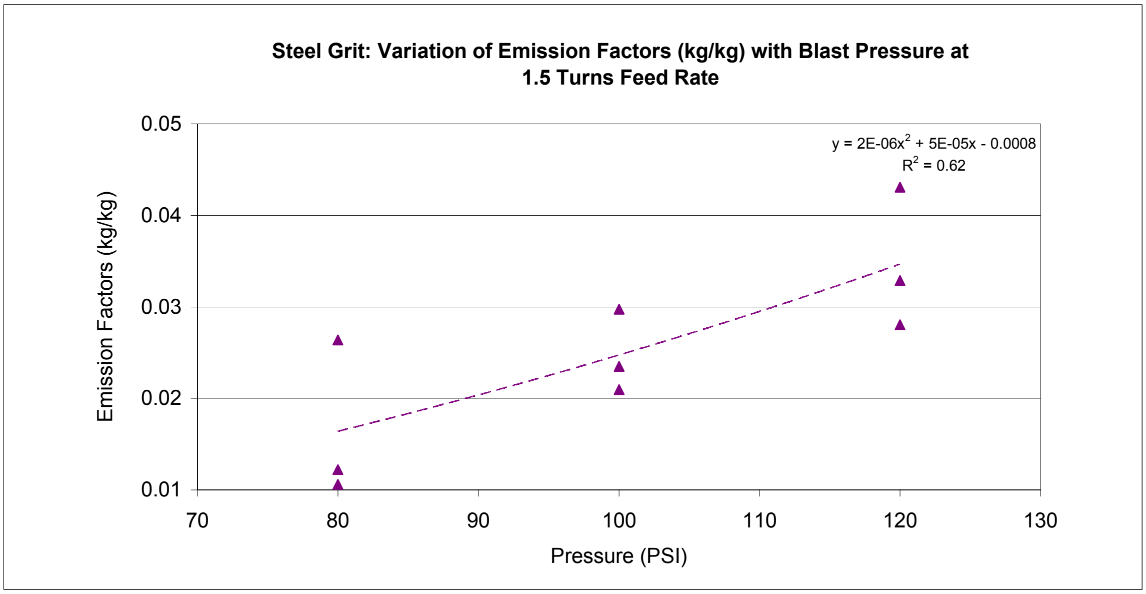


Figure 42 Variation of Emission Factors (kg/kg) with Blast Pressure at 1.5 turns Feed Rate

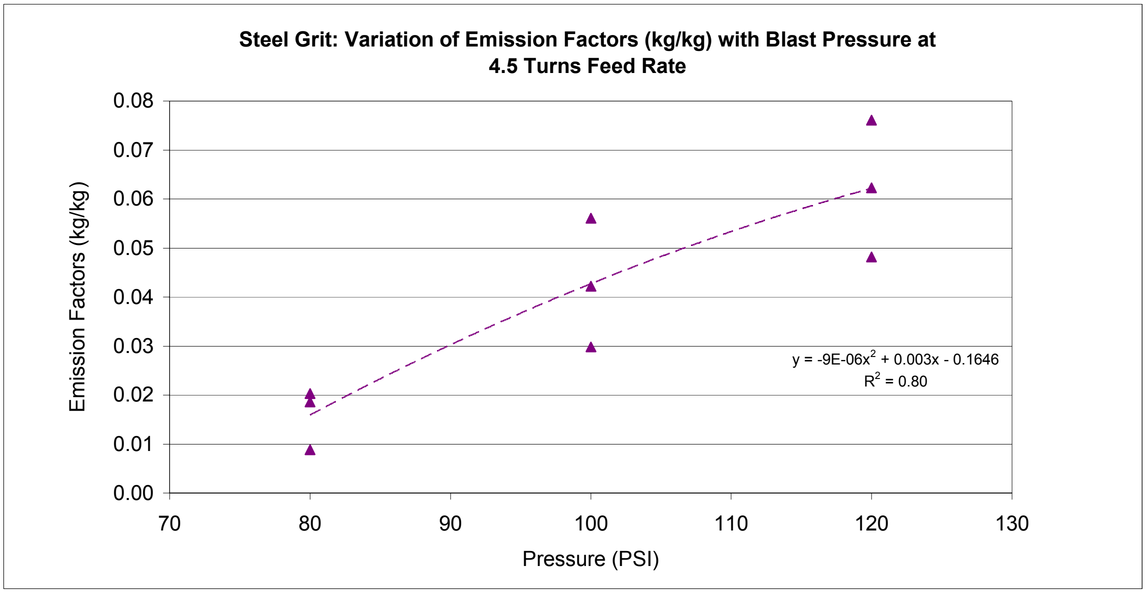


Figure 43 Variation of Emission Factors (kg/kg) with Blast Pressure at 4.5 turns Feed Rate

Garnet: Emission factors (kg/m^2) as seen in Figure 33 increased with blast pressure at a feed rate setting of three turns. This is because of the increase in momentum of the particles due to increase in pressure at a given mass flow rate. The velocity of the particles increases as a result of increase in pressure leading to increased particle breakdown which results in increased airborne particulates. The same trend is observed for mass based emission factors (kg/kg) at three turns feed rate. These relationships are strong as supported by the high correlation coefficients in both cases. At a feed rate of four turns, emission factors (kg/m^2) first decreased with pressure till 100 PSI and then increased till 120 PSI. This means that at four turns feed rate, increase in pressure first leads to reduction in emissions till 100 PSI and increase till 120 PSI again. This indicates that 100 PSI is the critical pressure where emission factors can be the lowest at four turns feed rate condition. Emission factors (kg/kg) however, increased with pressure at four turns feed rate from 80 to 100 PSI and remained constant henceforth. This may because, total particulate emissions increased with pressure for a given mass of abrasive consumed at this feed rate setting. At a feed rate of five turns, emission factors (kg/m^2) consistently decreased with pressure and this relationship is supported by a high correlation coefficient. Five turns condition corresponds to a high mass flow rate and increasing the pressure might have resulted in high rebound rates, less particle breakdown, and low emission potential. Also, at this feed rate, emission factors (kg/kg) decreased with blast pressure.

Steel grit/shot: Figures 33 – 42 show the variation of emission factors with pressure. At three turns feed rate condition both emission factors increased with pressure. From 36, and 37, it can be concluded that emission factors increase with blast pressure at 1.5 and 4.5 turns feed rate conditions. However, at 1.5 turns, emission factors (kg/m^2) did not increase significantly from 100 to 120 PSI. The same is true for emission factors expressed in kg/kg at 1.5 as well as 4.5 turns. This is shown in figures 41 and 42.

Barshot: Figures 33 to 42 shows the variation of emission factors (in kg/m^2 as well as kg/kg) with respect to blast pressure at the tested feed rate settings. It was observed that emission factors (kg/m^2) increased from three turns feed rate setting to four turns setting and then decreased till five turns. Emission factors (kg/kg) were observed to increase with blast pressure at all the three feed rate settings. This was the trend in most of cases as can be seen from the plots.

5.7 Parameter Variation with Blast Pressure and Abrasive Feed Rate

Since blast pressure and feed rate simultaneously influence emission factors, *multivariable regression analysis and two way ANOVA (Analysis of Variance)* techniques were employed to study the actual effect of these parameters on productivity, consumption and uncontrolled TPM emission factors. Datafit©, a statistical software package, was used to run multiple regression analysis and obtain three dimensional models to express performance parameters as function of blast pressure and abrasive feed rate. The details of the statistical analysis techniques have been discussed earlier. The following are the three dimensional plots obtained as a result of regression analysis and the models were chosen based on continuity of the plot, best found r^2 and 99% confidence intervals.

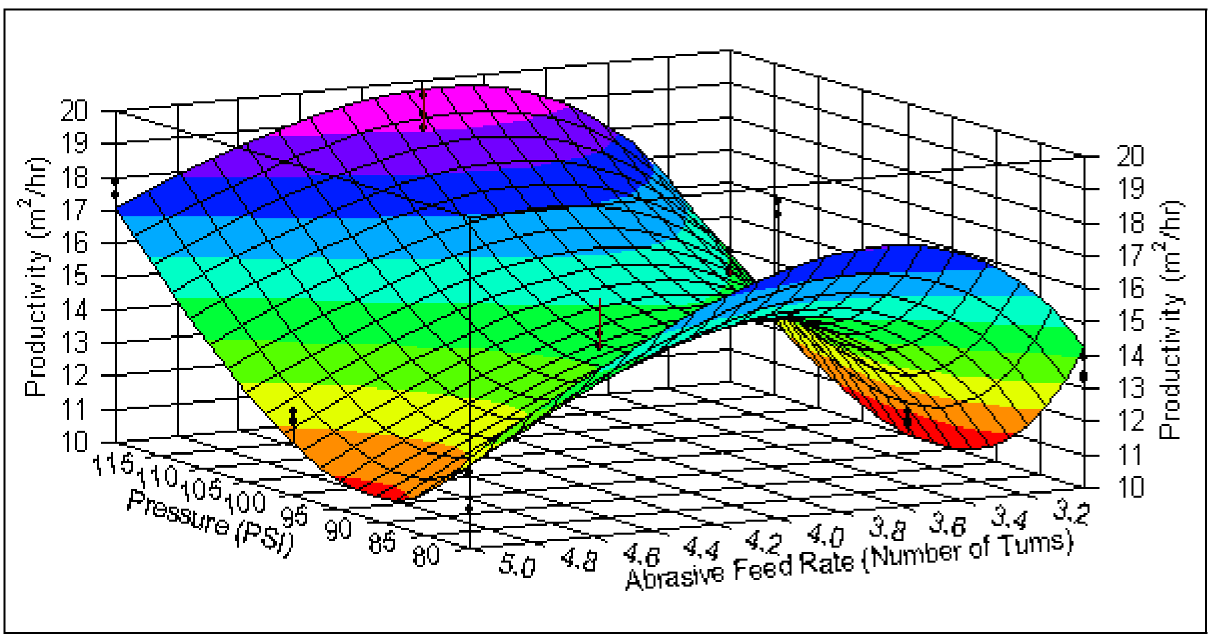


Figure 44 Barshot - Variation of Productivity with Pressure and Feed Rate

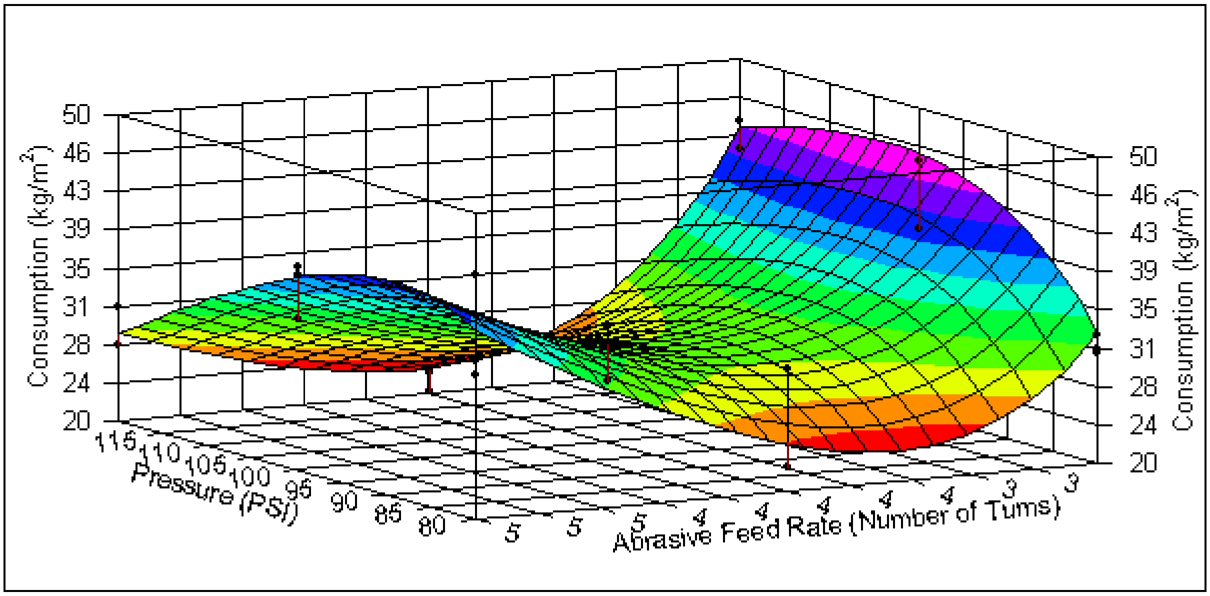


Figure 45 Barshot - Variation of Consumption with Pressure and Feed Rate

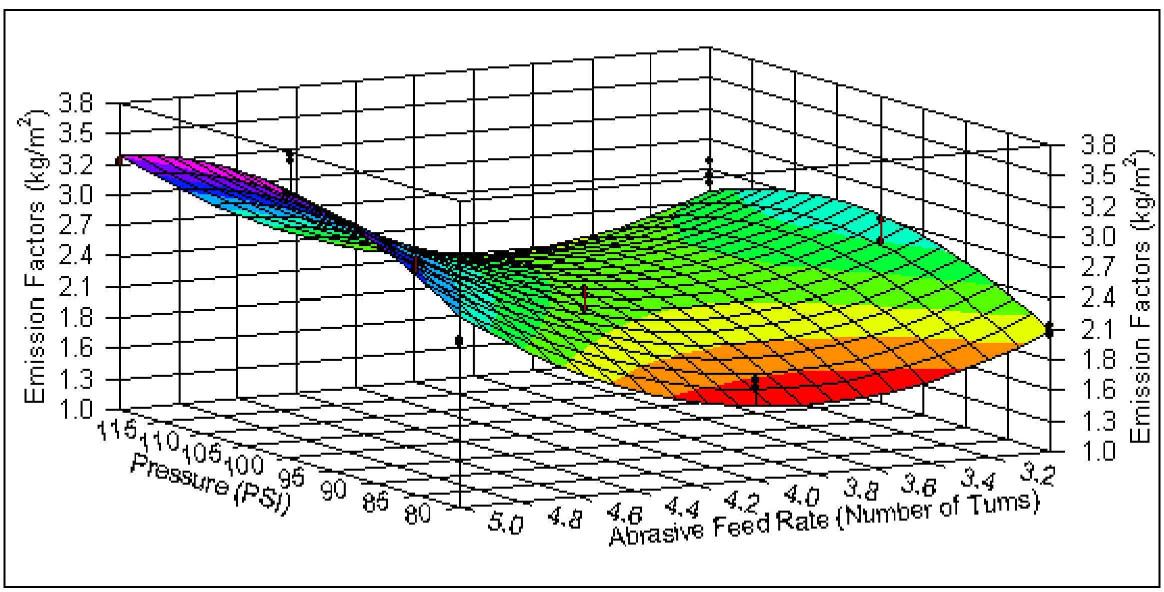


Figure 46 Barshot - Variation of Emission Factors (kg/m^2) with Pressure and Feed Rate

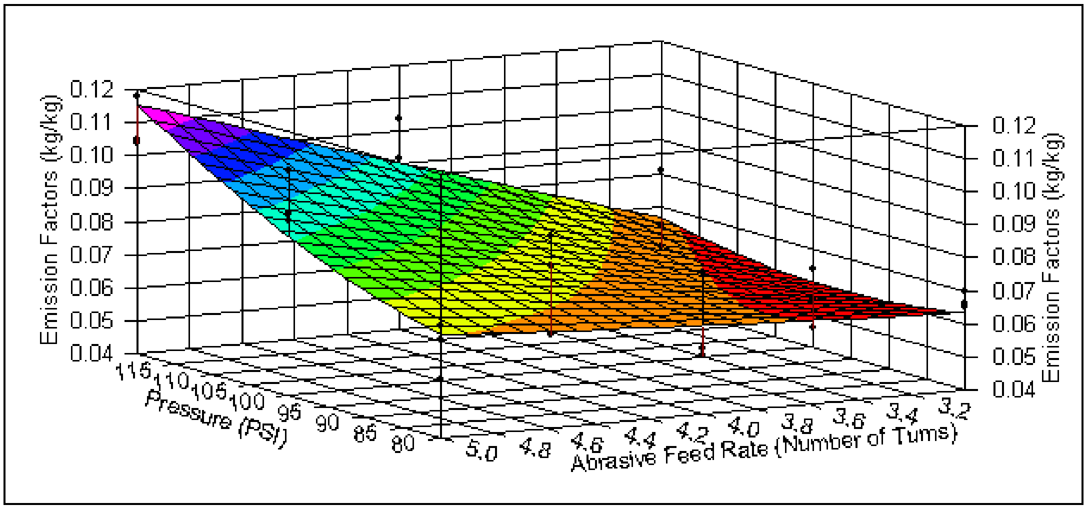


Figure 47 Barshot - Variation of Emission Factors (kg/kg) with Pressure and Feed Rate

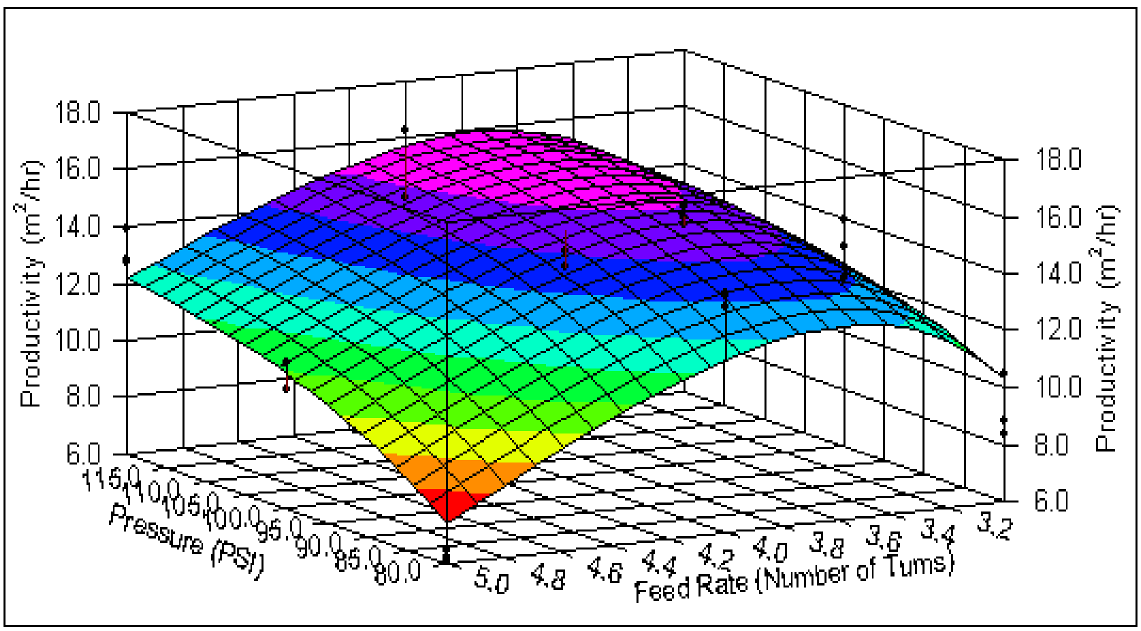


Figure 48 Garnet - Variation of Productivity with Pressure and Feed Rate

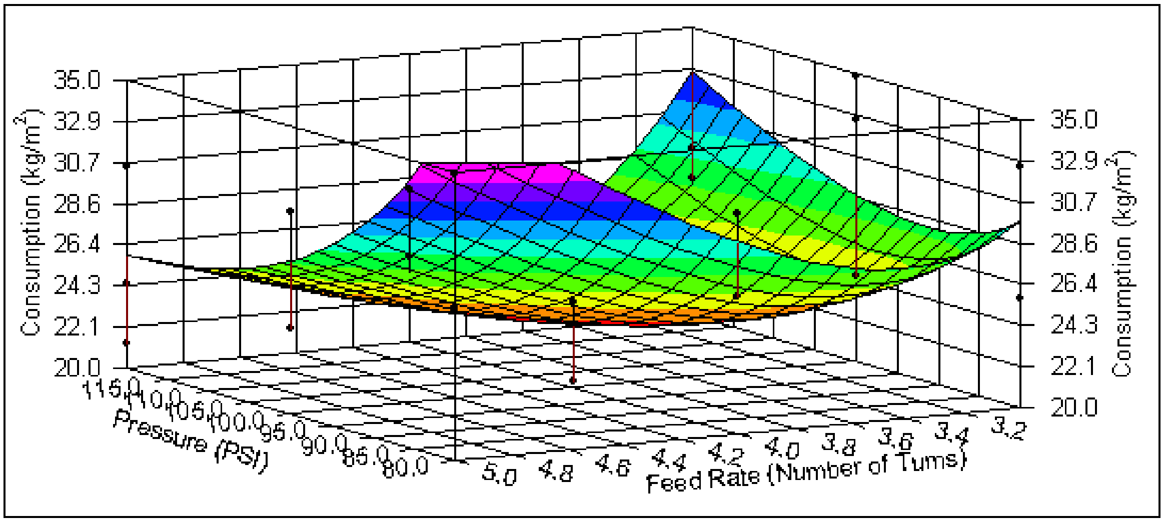


Figure 49 Garnet - Variation of Consumption with Pressure and Feed Rate

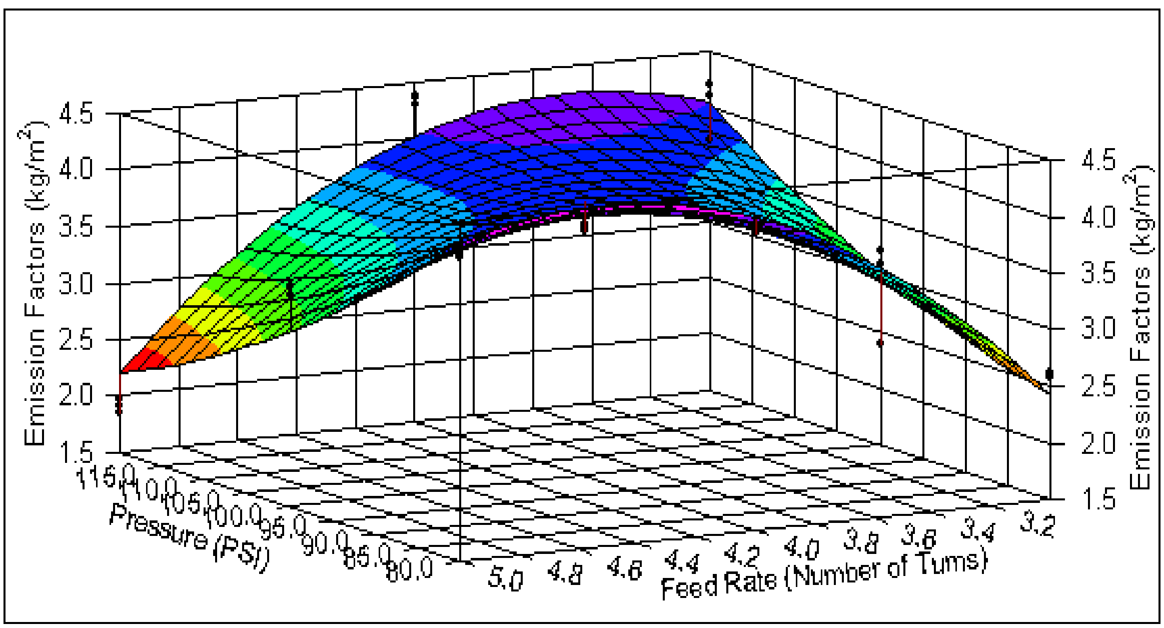


Figure 50 Garnet - Variation of Emission Factors (kg/m^2) with Pressure and Feed Rate

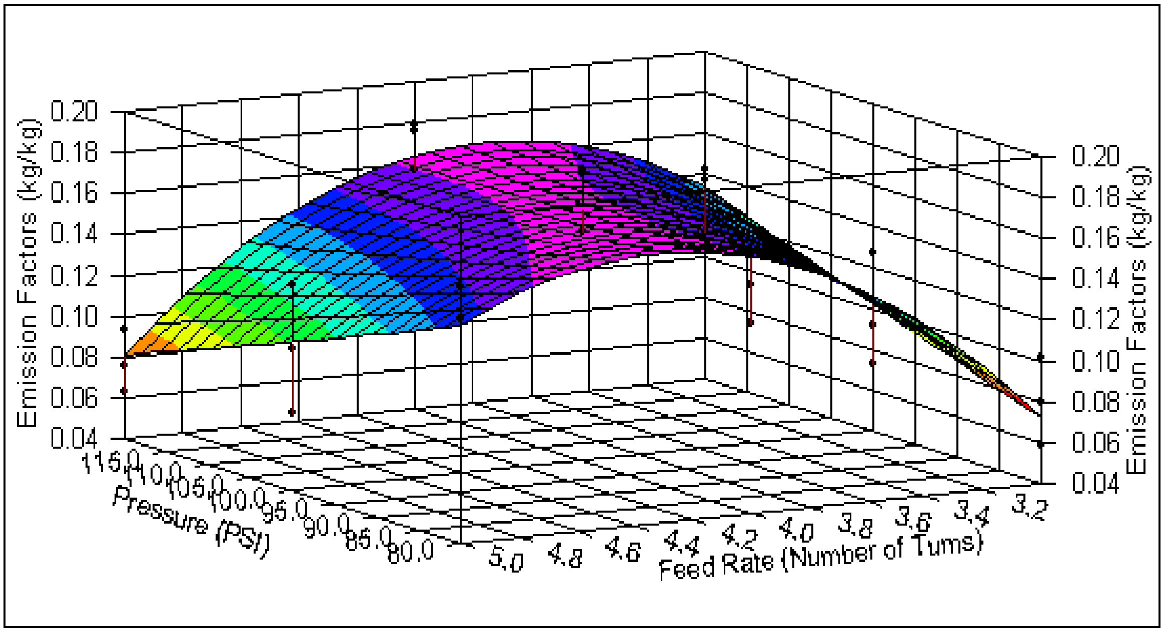


Figure 51 Garnet - Variation of Emission Factors (kg/kg) with Pressure and Feed Rate

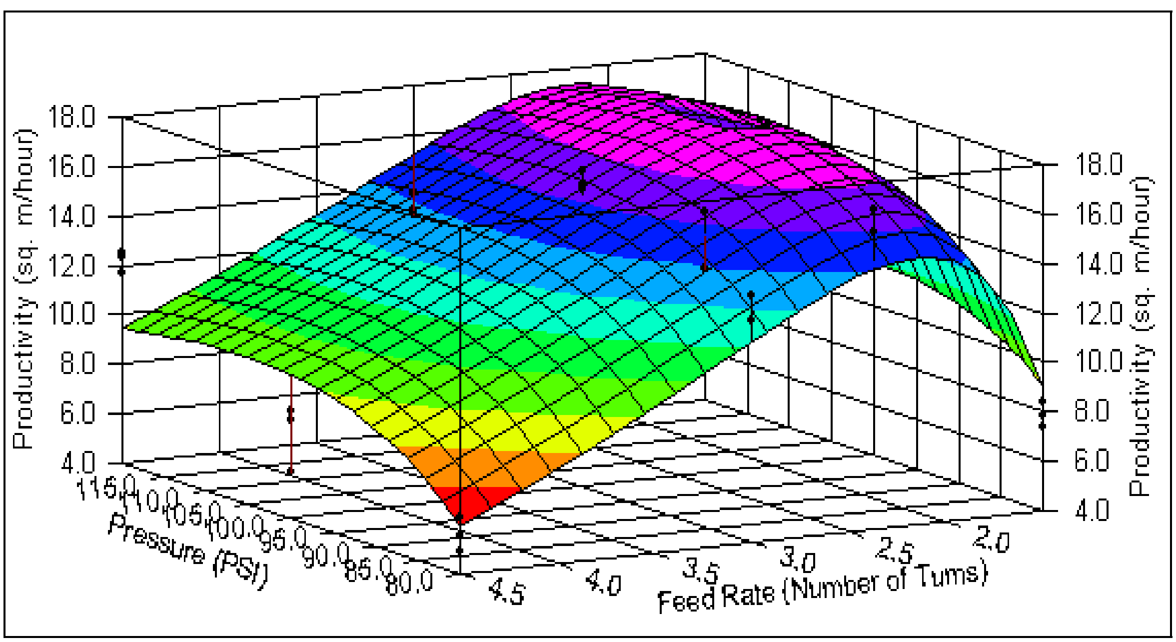


Figure 52 Steel Grit/Shot - Variation of Productivity with Pressure and Feed Rate

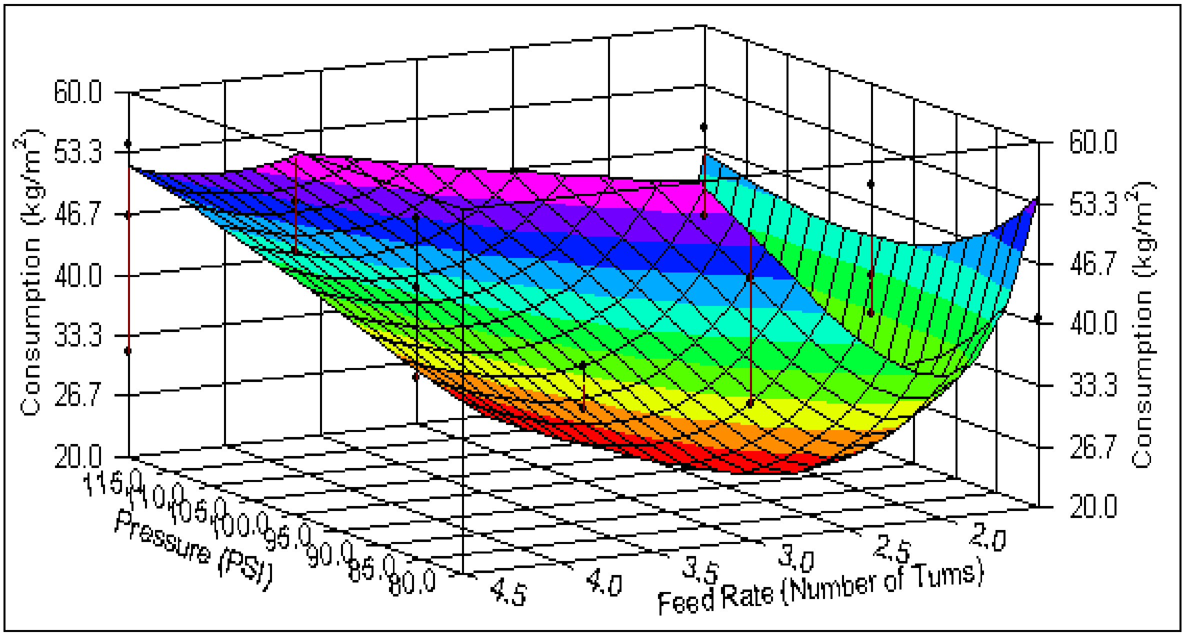


Figure 53 Steel Grit/Shot - Variation of Consumption with Pressure and Feed Rate

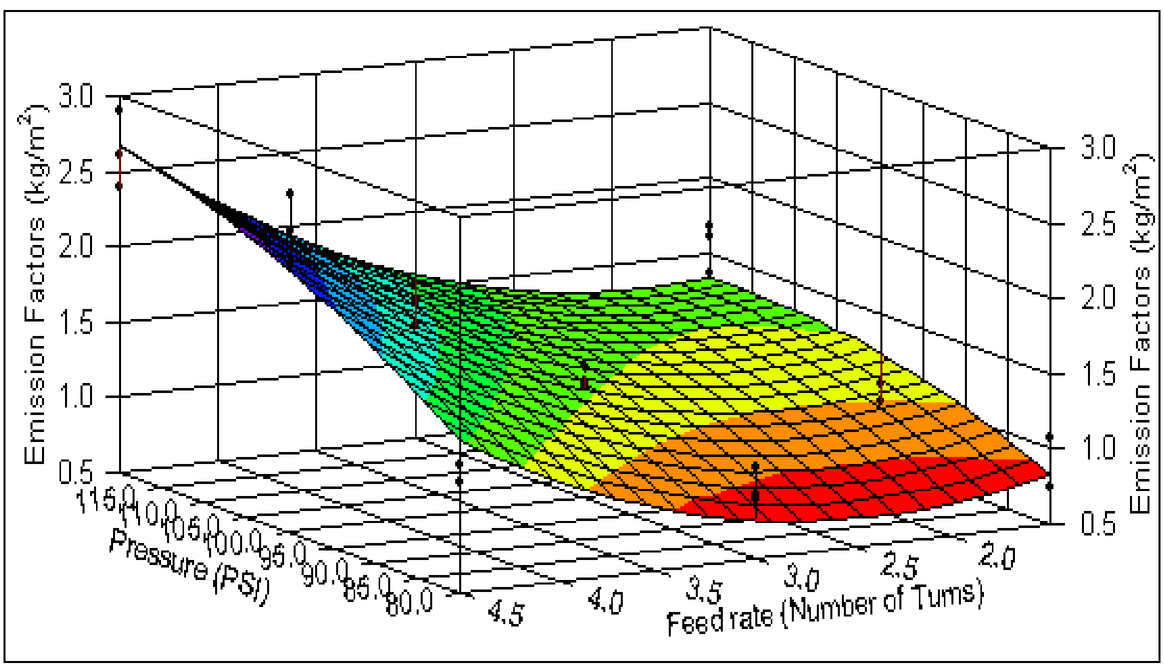


Figure 54 Steel Grit/Shot - Variation of Emission Factors (kg/m^2) with Pressure and Feed Rate

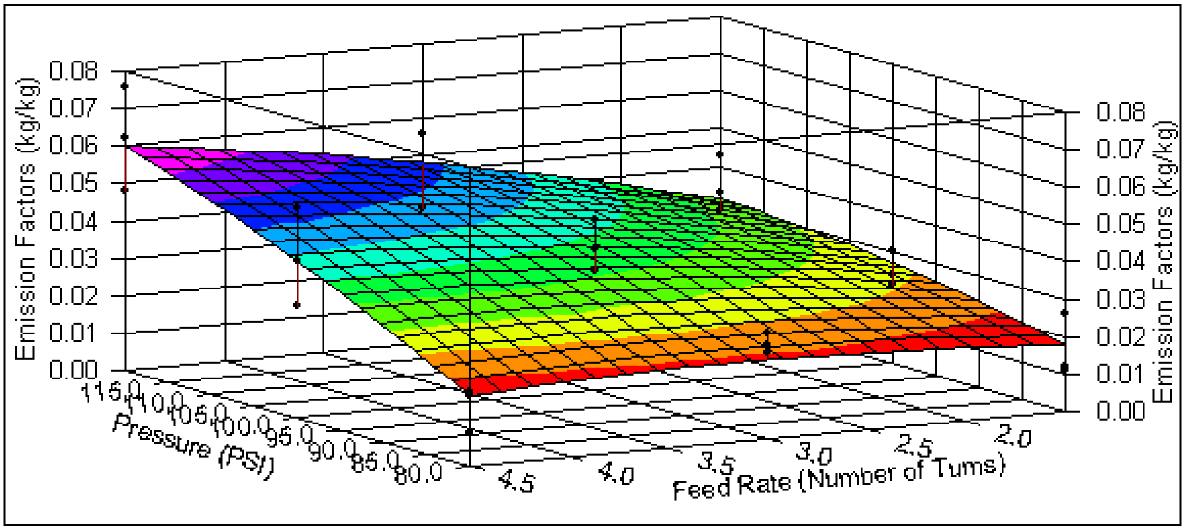


Figure 55 Steel Grit/Shot - Variation of Emission Factors (kg/m^2) with Pressure and Feed Rate

The following equation obtained based on Datafit model output, was found to be the single relationship that best expresses both productivity as well as consumption. Table 7 shows the appropriate coefficients to be used in equation for the various cases. These coefficients correspond to 99% confidence levels.

$$Y = a + \frac{b}{P} + \frac{c}{F} + \frac{d}{P^2} + \frac{e}{F^2} + \frac{f}{P*F} \quad (11)$$

Where,

Y = productivity (m^2/hr) or consumption (kg/m^2); to be read from Table 7,

P = blast pressure (PSI), applicable range: 80 – 120 PSI,

F = abrasive feed rate (# turns: 3 to 5 turns), and

a,b,c,d,e,f = coefficients to be read from Table 7.

Table 7 Coefficients for Productivity and Consumption Equation

Performance Parameter	Garnet						
	a	b	C	d	e	f	R^2
Productivity (m^2/hr)	-38.85	248.58	412.97	-116587	-855.43	5191.32	0.76
Consumption (kg/m^2)	94.50	-5607.64	-351.18	676297	1186.75	-27651.51	0.44
	Barshot						
	a	b	c	d	e	f	R^2
Productivity (m^2/hr)	75.72	-21734.2	416.30	904480	-976.8	9281.25	0.88
Consumption (kg/m^2)	-49.04	41891.61	-1074.41	-1545747	2794.79	-36650.59	0.78
	Steel grit / shot						
	a	b	C	d	e	f	R^2
Productivity (m^2/hr)	-48.12	7743.46	125.32	-423200	-147.13	997.87	0.72
Consumption (kg/m^2)	209.47	-18944.7	-483.07	1455805	662.07	-14174.30	0.53

Equation 12 obtained based on Datafit model output, was found to be the single relationship that best expresses uncontrolled TPM emission factors (kg/m^2 as well as kg/kg) as function of blast pressure and abrasive feed rate (#turns). Table 8 shows the appropriate coefficients to be used in equation for the various cases. These coefficients correspond to 99% confidence levels.

$$EF = a + (b * P) + (c * F) + (d * P^2) + (e * F^2) + (f * P * F) \qquad (12)$$

where:

EF = uncontrolled TPM emission factor (kg/m^2 or kg/kg) to be read from Table 8,

P = blast pressure (PSI), applicable range: 80 – 120 PSI,

F = feed rate (# turns), applicable range: 3 to 5 turns, and

a,b,c,d,e,f = coefficients to be read from Table 8.

Table 8 Coefficients for Uncontrolled TPM Emission Factors Equation

Performance Parameter	Garnet						
	a	B	C	D	e	f	r^2
Emission Factor (kg/m^2)	-23.28	0.08	11.85	0.0005	-0.90	-0.0466	0.89
Emission Factor (kg/kg)	-1.36	0.01	0.61	0.000002	-0.06	-0.0016	0.77
	Barshot						
	a	B	C	D	e	f	r^2
Emission Factor (kg/m^2)	2.34	0.21	-5.91	-0.0010	0.75	0.0025	0.90
Emission Factor (kg/kg)	0.30	-0.0040	-0.04	0.000013	0.0004	0.0005	0.75
	Steel grit / shot						
	a	B	C	D	e	f	r^2
Emission Factor (kg/m^2)	-2.29	0.08	-1.32	-0.0004	0.18	0.0055	0.87
Emission Factor (kg/kg)	-0.05	0.0013	-0.01	-0.000007	-0.0012	0.0002	0.75

5.8 Application of Results: Life Cycle Cost Estimation and Optimization

Process costs and overall life cycle costs for dry abrasive blasting process depend on the productivity, consumption and particulate emissions from the process. Life costs of dry abrasive blasting process can be classified as direct and indirect costs. Both these cost components are influenced by cleaning rates (productivity) and material usage (consumption) and pollution generation (particulate emissions). The following equations describe the various cost components as a function of performance parameters. For convenience, all the costs have been defined and calculations done on a 1000 m^2 blasted area basis.

$$\text{Life Cycle Costs } (\$/1000\ m^2) = \text{Direct Costs } (\$/1000\ m^2) + \text{Indirect Costs } (\$/1000\ m^2) \quad \text{----- (13)}$$

Total Direct Costs = Total Equipment Cost + Total Labor Cost + Total Material Cost + Total Energy Cost ------ (14)

$$\text{Total Equipment Cost (\$)} = \sum_{i=1}^{n} \left\{ \frac{\{CapitalCost_i(\$) - \text{Re}\,sidualValue_i(\$)\} * 1000(m^2)}{\text{Pr}\,oductivity(m^2/hr) * Numberofhours_i} \right\}$$
------- (15)

$$TotalLaborCost(\$) = \frac{CostofLabor(\$/hr) * 1000(m^2)}{\text{Pr}\,oductivity(m^2/hr)}$$
------- (16)

$$TotalMaterialCost(\$) = \frac{MaterialCost(\$/kg) * ConsumptionRate(kg/m^2)}{Numberof\ \text{Re}\,uses}$$
------- (17)

$$TotalEnergyCost = \frac{1000 * SumofPowerRatings(kWh) * EnergyCost(\$/kWh)}{\text{Pr}\,oductivity(m^2/hr)}$$
------- (18)

Total Indirect Costs = Permit & Compliance Cost + Total Emission Cost + Total Disposal Cost
------- (19)

$$TotalEmissionCost = \sum EmissionCosts(\$/kg) * ConsumptionRate(kg/m^2) * 1000m^2$$
------- (20)

$$TotalDisposalCost = \sum DisposalCosts(\$/kg) * ConsumptionRate(kg/m^2) * 1000m^2$$
-------- (21)

Labor cost and material cost data are available from the US department of labor and respective abrasive suppliers from the respective states. Power ratings can be obtained for the individual equipment such as compressors, blast pots, pressure hoses, etc. Permit and compliance cost information for individual facilities located in various states can be obtained from appropriate regulatory agency sources. Hence, it can be clearly seen that both the direct and indirect cost components are functions of productivity, consumption and emission factors which in turn are functions of blast pressure and abrasive feed rate and discussed earlier. Therefore, expressing life cycle costs in terms of pressure and abrasive feed is one of the significant applications of this study. This will help industry and regulatory agencies and scientists to

1. Evaluate life cycle costs at various operating conditions.
2. Minimize life cycle costs by choosing best operating conditions of pressure, feed rate.
3. Determine life cycle costs at pressure and feed rate conditions corresponding to highest productivity conditions. The highest productivity conditions can be obtained my numerically optimizing the productivity function for each abrasive.
4. Determine life cycle costs at pressure and feed rate conditions corresponding to lowest consumption rates. The least consumption conditions can be obtained my numerically optimizing the consumption function for each abrasive.
5. Determine life cycle costs at pressure and feed rate conditions corresponding to lowest emission rates. The lowest emission scenarios can be obtained my numerically optimizing the emission factors function for each abrasive.
6. Identify and implement BMPs (Best Management Practices) that correspond to least costs and emissions.

An example of how the models developed can be used for direct and indirect cost estimations for the studied abrasives is shown in Appendix D.

6.0 Conclusions

This study was carried out at the emission testing facility at the University of New Orleans to evaluate the productivity (m^2/hr), consumption (kg/m^2) and Uncontrolled TPM emission factors (expressed in kg/m^2 and kg/kg), observe and model relationships between these performance parameters as functions of blast pressure and abrasive feed rate, the two most critical parameters influencing them. Blasting was conducted in an enclosed chamber of size 12'x10'x8'. The substrates used were mild steel plates painted with marine paint (Rust Oleum Safety Yellow ©) and thinner mixture using spray guns and hand rollers to obtain and average paint thickness of 0.76 mils. A standard number 6 Bazooka nozzle was used for blasting. Blasting was carried out at pressures of 80, 100 and 120 PSI and at feed rate settings corresponding to 3, 4 and 5 turns open condition of Schmidt feed valve. The emissions from the blast chamber vented through an exhaust duct using a variable speed exhaust fan operated at 60 rpm providing an average volumetric flow rate of 3000 cfm.

It should be noted that the abrasives were not recycled and the results and models presented correspond to the first time use of virgin abrasives. The models presented in this paper are applicable only within the tested ranges of blast pressure, abrasive feed rate and conditions mentioned at the beginning of this chapter. Due care should be exercised while using these models to make estimates outside these specified ranges.

1. This study enabled generation of data for performance parameters of bar shot, garnet and steel grit/shot used for blasting of painted steel panels using standardized testing protocols. This will greatly help filling data gaps in productivity, consumption and emission factor literature.
2. This study also enabled identifying and quantifying the relationships of performance parameters as function of blast pressure and abrasive feed rate, a major task in source characterization in the abrasive blasting process category.
3. The following model was obtained to predict productivity and consumption as function of blast pressure and abrasive feed rate:

$$Y = a + \frac{b}{P} + \frac{c}{F} + \frac{d}{P^2} + \frac{e}{F^2} + \frac{f}{P * F}$$

   Where,

   Y = productivity (m^2/hr) or consumption (kg/m^2),

   P = blast pressure (PSI), applicable range: 80 – 120 PSI,

   F = abrasive feed rate (# turns: 3 to 5 turns), and

   a,b,c,d,e,f = coefficients in parameter equation.

4. The following model was obtained to predict uncontrolled TPM emission factors as function of blast pressure and abrasive feed rate:

$$EF = a + (b * P) + (c * F) + (d * P^2) + (e * F^2) + (f * P * F)$$

where:

EF = uncontrolled TPM emission factors (kg/m^2 or kg/kg),

P = blast pressure (PSI), applicable range: 80 – 120 PSI,

F = feed rate (# turns), applicable range: 3 to 5 turns, and

a,b,c,d,e,f = coefficients in parameter equation.

5. Using the models obtained from this study, productivity and consumption can be predicted at any pressure, abrasive feed rate condition within the tested ranges and at the tested conditions.
6. Uncontrolled TPM emissions can be estimated using the findings of this research and this will help industries and regulatory agencies obtain emission estimates with better data quality ranking.
7. The developed two and three dimensional models presented will help in assessing the maximum productivity and minimum consumption and emission scenarios for the three abrasives.
8. The findings of this study will help in identifying and optimizing process conditions (*best management* practices) to minimize consumption, solid waste generation and particulate emissions.
9. Higher productivity results in less energy, labor, depreciation costs, less consumption of energy as well as less down time due to repair. Lower consumption means using less material to clean the area and thus less solid/hazardous waste to be disposed of, resulting in reduction in material costs and disposal costs. Hence the proposed models will be useful in identifying the best process conditions to minimize emission, disposal and

environmental costs thereby the overall process lifecycle costs for abrasive blasting process.

10. Industries, regulatory agencies, and scientific groups will be able to use these models in particulate emissions estimation, air permitting, compliance evaluation, risk assessment, and development of best management practices.
11. These results will enhance studies aimed at assessment of health risk assessments associated with inhaled particulates resulting from steel grit or steel shot blasting.
12. The emission estimation models developed in this research will help in evaluating emission potential of the abrasives at various operating conditions and ranking the abrasives at a particular feed rate, pressure condition.
13. The overall performance trends can be summarized as follows:

- Productivity:
    - 80 PSI: barshot > garnet > steel grit/shot
    - 100 PSI: steel grit/shot > barshot > garnet
    - 120 PSI: barshot > garnet > steel grit/shot
    - 3 turns: steel grit/shot > garnet > barshot
    - 4 turns: barshot > garnet
    - 5 turns: bar shot > garnet

It can be concluded that at 100 PSI and at 3 turns steel grit showed a better productivity than the other 2 abrasives. Bar shot showed the highest productivity at the other conditions.

- Consumption:
    - 80 PSI: steel grit/shot > barshot > garnet

- 100 PSI: barshot > steel grit/shot > garnet
- 120 PSI: steel grit/shot > barshot > garnet
- 3 turns: barshot > steel grit/shot > garnet
- 4 turns: barshot > garnet
- 5 turns: bar shot > garnet

It can be concluded from above that garnet showed the least consumption rates at comparable conditions.

7.0 Recommendations

1. Further research can be undertaken to evaluate the particle size distribution in the particulate filter samples collected from the stack in this study
2. Further research can be undertaken to determine the metal speciation in the particulate filter samples collected from the stack in this study
3. Productivity, consumption and uncontrolled TPM emission factors should be evaluated for multiple passes of abrasives (reuse of abrasives multiple times).
4. Productivity, consumption and uncontrolled TPM emission factors should be evaluated for varying paint thicknesses.
5. Productivity, consumption and uncontrolled TPM emission factors should be evaluated for varying fan capacities.

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Appendices

Appendix A

Stack Monitoring Field Observation Data Sheets

Stack Monitoring Field Observation Data Sheet

Site Location: Emission Test Facility, University of New Orleans

BS/80/3/1

Blast Time	6	**Pressure:**	80
Area ft^2	14.25	**Turns:**	3
Leak Check	OK	**Run No:**	1
K factor	1.10	**Finish**	Near White
Abrasive Mass	90		
Initial DGM Reading (cf)	**349.290**		

Traverse Pt	DGM Reading	ΔP	ΔH	T $_{DGM,in}$	T $_{DGM,out}$	T $_{DGM,avg}$		T$_{stack}$	Vacuum	Hot Box Temp (F)	Cold Box Temp (F)
	(cf)	(in H_20)	(in H_20)	(F)	(F)	(F)		(F)	(in Hg)		
1	350.100	0.69	0.76	101.0	101.0	101.0	40.0	104.0	5.0	140	72
2	350.980	0.75	0.82	101.0	101.0	101.0	35.0	95.0	5.0	155	70
3	351.970	0.87	0.96	102.0	101.0	101.5	35.0	95.0	7.0	170	68
4	353.040	1.00	1.10	102.0	101.0	101.5	35.0	95.0	7.0	180	65
5	354.190	1.20	1.32	103.0	102.0	102.5	35.0	95.0	10.0	195	63
6	355.390	1.20	1.32	104.0	103.0	103.5	35.0	95.0	10.0	200	62
7	356.630	1.30	1.43	104.0	103.0	103.5	35.0	95.0	10.0	195	60
8	357.990	1.10	1.21	104.0	104.0	104.0	35.0	95.0	10.0	185	60
	ΔP$_{avg}$	**1.01**	**1.11**		**Average**	**102.3**	**35.0**	**96.1**			

Impinger Data	Impinger 1	Impinger2	Impinger 3	Impinger 4
Final	559.5	591.5	433.5	559
Initial	556.5	589	432.5	556.5
Difference	3	2.5	1	2.5
		Filter	Beaker	

Total Mass Collected	Initial Mass	0.8145	105.3024	Gm
	Final Mass	0.8222	105.8323	Gm
	Mass Collected	0.0077	0.5299	Gm

Symbol	Description	Comments	Units	Value
V1	Initial Meter Reading		dcf	349.29
V2	Final Meter Reading		dcf	357.99
Vm	Actual Volume of gas measured by the DGM	(Final-Initial) meter reading	dcf	8.70
Tstd	Standard Temperature	$20^oC = 293^oK$	R	527.70
	Conversion factor (in.of Hg to mm.of Hg)			25.40
Y	Y(DGM correction factor: 0.95-1.05)	From DGM Calibration		0.99
P_B	Barometric Pressure	from weather report	in Hg	30.06
Δ P	Average Δ P		in. H20	1.01
		Δ P/13.6	in Hg	0.07
Pstd	Standard Pressure		mm Hg	760.00
Δ H@	Reference Δ H	From DGM Calibration	in. H20	1.80
K	K Factor for Δ H	Assuming Pdgm ~ Pbar		1.10
Δ H	Average Δ H	K*Δ P	in. H20	1.11
Pdgm	Pressure of DGM	P_B +Δ P/13.6	in Hg	30.13
Tdgm	Temperature of the DGM		F	102.31
Vm(std)	Volume of gas at standard conditions	$\frac{Vm*Y*(P_B+(\Delta P/13.6))*25.4*Tstd}{Pstd*(Tdgm+459.69)}$	DSCF	8.14
$V_{W,cond}$	Water collected in the 3 impingers		ml	6.50
$V_{W, SG}$	Mass Increase in silica gel impinger	_	Gm	2.50
$V_{w,cond(std)}$	Vol. of water vapour at Standard Conditions	K*(Vw) where K=0.04707 std ft^3/mL	scf	0.31
$V_{w,sg(std)}$	Vol. of water vapour absorbed on Silica Gel at Standard Conditions	K*(Vw) where K=0.04715 std ft3/g	scf	0.12
B_{H20}	Percent Moisture Content by Volume			0.05
P_{MOS}	Mole Fraction of Dry Gas		--	0.96
MW_D	Molecular Weight Dry Gas		--	29.84

MWw	Wet Stack Gas	$M_{gas} = M_{dry}$ X $(1-B_{H2O})$ + (18 X B_{H2O})	--	28.77
DPS	√(ΔP)		in H20	1.01
T_S	Average Stack Temp		DEG F	96.13
P_S	Stack Pressure Absolute	P_B +Δ P (in Hg)	in Hg	30.13
Cp	Pitot Tube Coeff			0.84
V_S	Average Stack Gas Velocity	Kp * Cp* sqrt(Tgas/(Ps*MWw))*sqrt(Δ P) where Kp = 85.49* 60	fpm	3473.71
Dia(stack)	Inside Diameter of Stack		In	12.00
Astack	Stack Area(sq.in)		sq in.	113.10
Astack	Stack Area(sq ft)		sq.ft	0.79
Qactual	Stack Flow Rate Actual Conditions	Vs*As	cfm	2728.25
Qstd	Stack Flow Rate Dry, Std Conditions	$\frac{(Qactual*Pactual*Tstd)}{(Tactual*Pstd*B_{H2O})}$	dscfm	2706.81
TT	Net time of run	sampling time = (2min*8 traverse points)	min	16.00
Dia(nozzle)	Nozzle Diameter		In	0.18
Anozzle	Nozzle Area		sqft	0.0002
% Iso-Kinetic	Percent Isokinetic	$\frac{100*(Ts+459.69)*Vm(std)*Pstd}{(Tstd*Vs*TT*Ps*25.4*MF_D*Anozzle)}$	%	**89.89**
MF	Particulate Weight (Total)	filter(final wt-initial wt)	Gm	0.5376
q_{std}	gas flow collected at standard conditions	$V_{m(std)}$ / TT	dscfm	0.51
EF_{std} (grams)			Gm	2861.75

Appendix B

Statistical Analysis

Bar Shot Productivity Data

Pressure (PSI)	Turns	Productivity (m^2/hr)
120	3	13.94
120	3	13.94
120	3	13.24
120	4	18.58
120	4	18.95
120	4	19.51
120	5	17.84
120	5	17.42
120	5	17.42
100	3	10.31
100	3	10.45
100	3	10.68
100	4	13.59
100	4	13.94
100	4	13.94
100	5	12.26
100	5	12.2
100	5	12.54
80	3	13.24
80	3	13.38
80	3	13.94
80	4	19.17
80	4	19.51
80	4	19.51
80	5	11.15
80	5	11.15
80	5	12.26

Datafit© Regression Analysis Output

Model Definition:
Y = a+b/x1+c/x2+d/x1^2+e/x2^2+f/(x1*x2)

Number of observations = 27
Number of missing observations = 0
Solver type: Nonlinear
Nonlinear iteration limit = 250
Diverging nonlinear iteration limit =10
Number of nonlinear iterations performed = 6
Residual tolerance = 0.0000000001
Sum of Residuals = 3.81916720471054E-13
Average Residual = 1.41450637211501E-14
Residual Sum of Squares (Absolute) = 30.2316407805227
Residual Sum of Squares (Relative) = 30.2316407805227
Standard Error of the Estimate = 1.19983413100714
Coefficient of Multiple Determination (R^2) = 0.8830552983
Proportion of Variance Explained = 88.30552983%
Adjusted coefficient of multiple determination (Ra^2) = 0.8552113217
Durbin-Watson statistic = 1.16813518556354

Regression Variable Results

					68% Confidence Intervals				
Variable	Value	Standard Error	t-ratio	Prob(t)	Variable	Value	68% (+/-)	Lower Limit	Upper Limit
a	75.72273	16.56685793	4.570735549	0.00017	a	75.72273	16.875	58.84772497	92.59772794
b	-21734.2	2565.817075	-8.47068821	0	b	-21734.2	2613.541	-24347.7772	-19120.6958
c	416.3027	68.86804862	6.044933146	0.00001	c	416.3027	70.14899	346.1537554	486.4517441
d	904480	118340.3893	7.643037219	0	d	904480	120541.5	783938.4794	1025021.521
e	-976.8	118.7775191	-8.22377843	0	e	-976.8	120.9868	-1097.78678	-855.813219
f	9281.246	2451.938085	3.785269304	0.00108	f	9281.246	2497.544	6783.701836	11778.7901

90% Confidence Intervals					95% Confidence Intervals				
Variable	Value	90% (+/-)	Lower Limit	Upper Limit	Variable	Value	95% (+/-)	Lower Limit	Upper Limit
a	75.72273	28.50659243	47.21613402	104.2293189	a	75.72273	34.45244	41.27028871	110.1751642

b	-21734.2	4415.00144	-26149.2379	-17319.2350	b	-21734.2	5335.873	-27070.1096	-16398.3633
c	416.3027	118.5012513	297.8014985	534.804001	c	416.3027	143.218	273.0847559	559.5207437
d	904480	203628.3079	700851.6921	1108108.308	d	904480	246100.7	658379.3264	1150580.674
e	-976.8	204.3804772	-1181.18048	-772.419523	e	-976.8	247.0097	-1223.80972	-729.790271
f	9281.246	4219.049864	5062.196107	13500.29583	f	9281.246	5099.05	4182.195528	14380.29641

99% Confidence Intervals

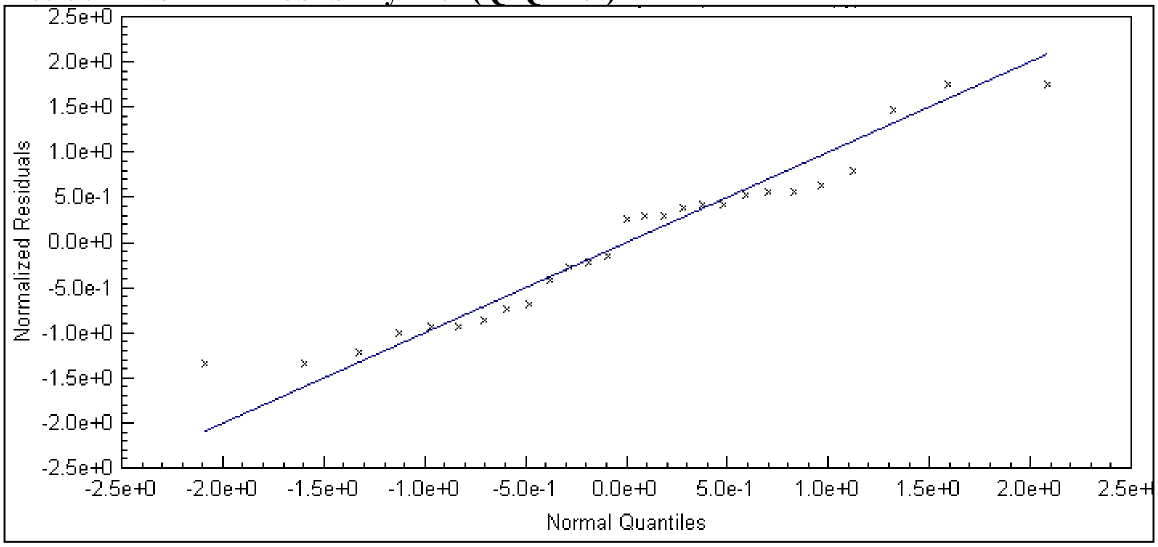
Variable	Value	99% (+/-)	Lower Limit	Upper Limit
a	75.72273	46.90740153	28.81532492	122.630128
b	-21734.2	7264.854465	-28999.0909	-14469.3819
c	416.3027	194.9929928	221.3097569	611.2957426
d	904480	335068.9783	569411.0217	1239548.978
e	-976.8	336.3066677	-1313.10667	-640.493332
f	9281.246	6942.417495	2338.828475	16223.66347

Variance Analysis				
Source	DF	Sum of Squares	Mean Square	F Ratio
Regression	5	228.2806333	45.65612666	31.7144103
Error	21	30.23164078	1.439601942	
Total	26	258.5122741		

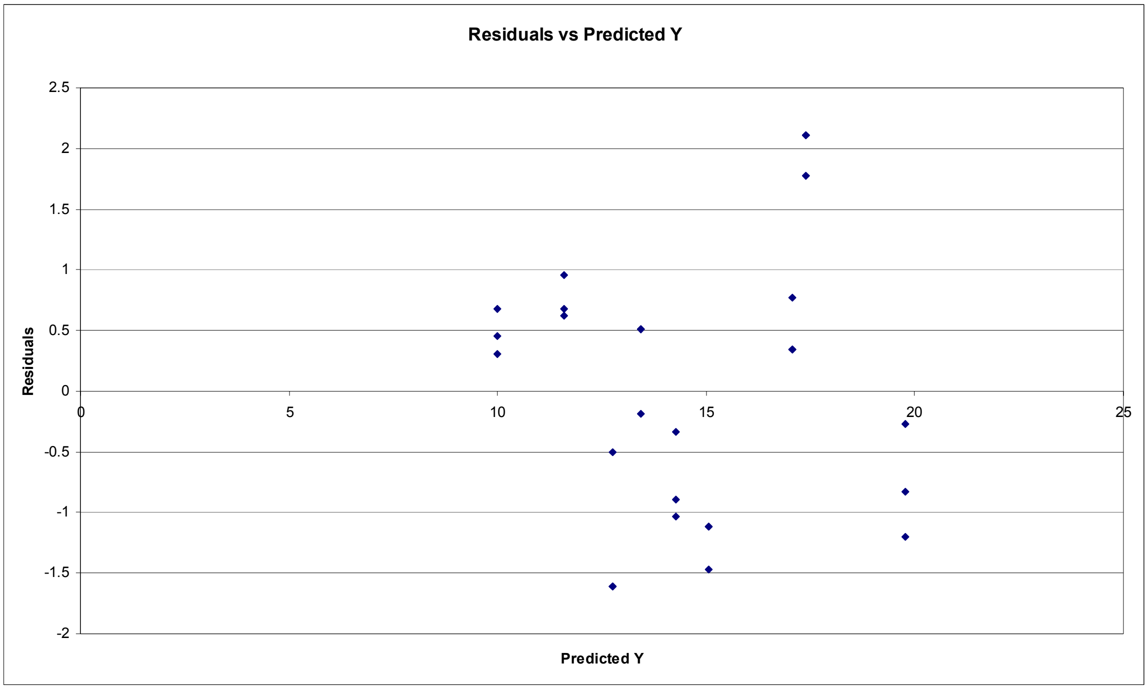
Residual Analysis

Pressure	Feed Rate	Productivity	Calculated Productivity	Residual	% Error	Absolute Residual	Min Residual	Max Residual
120	3	13.94	13.43068922	0.509310777	3.653592372	0.509310777	-1.611435732	2.110648049
120	3	13.94	13.43068922	0.509310777	3.653592372	0.509310777		
120	3	13.24	13.43068922	-0.19068922	-1.44025093	0.190689223		
120	4	18.58	19.77681704	-1.19681704	-6.44142649	1.196817043		
120	4	18.95	19.77681704	-0.82681704	-4.36315062	0.826817043		
120	4	19.51	19.77681704	-0.26681704	-1.36759119	0.266817043		
120	5	17.84	17.07249373	0.767506266	4.302165168	0.767506266		
120	5	17.42	17.07249373	0.347506266	1.994869494	0.347506266		
120	5	17.42	17.07249373	0.347506266	1.994869494	0.347506266		
100	3	10.31	10.00009846	0.30990154	3.005834525	0.30990154		
100	3	10.45	10.00009846	0.44990154	4.30527789	0.44990154		
100	3	10.68	10.00009846	0.67990154	6.366119284	0.67990154		
100	4	13.59	15.05716434	-1.46716433	-10.7959112	1.467164339		
100	4	13.94	15.05716434	-1.11716433	-8.01409138	1.117164339		
100	4	13.94	15.05716434	-1.11716433	-8.01409138	1.117164339		
100	5	12.26	11.57940387	0.680596133	5.551355083	0.680596133		
100	5	12.2	11.57940387	0.620596133	5.086853551	0.620596133		
100	5	12.54	11.57940387	0.960596133	7.660256246	0.960596133		
80	3	13.24	14.27587898	-1.03587898	-7.82385938	1.035878983		
80	3	13.38	14.27587898	-0.89587898	-6.6956575	0.895878983		
80	3	13.94	14.27587898	-0.33587898	-2.40946185	0.335878983		
80	4	19.17	17.39935195	1.770648049	9.236557374	1.770648049		
80	4	19.51	17.39935195	2.110648049	10.81828831	2.110648049		
80	4	19.51	17.39935195	2.110648049	10.81828831	2.110648049		
80	5	11.15	12.76143573	-1.61143573	-14.4523384	1.611435732		
80	5	11.15	12.76143573	-1.61143573	-14.4523384	1.611435732		
80	5	12.26	12.76143573	-0.50143573	-4.09001413	0.501435732		

Residual Normal Probability Plot (Q-Q Plot)



Residuals vs Predicted Y

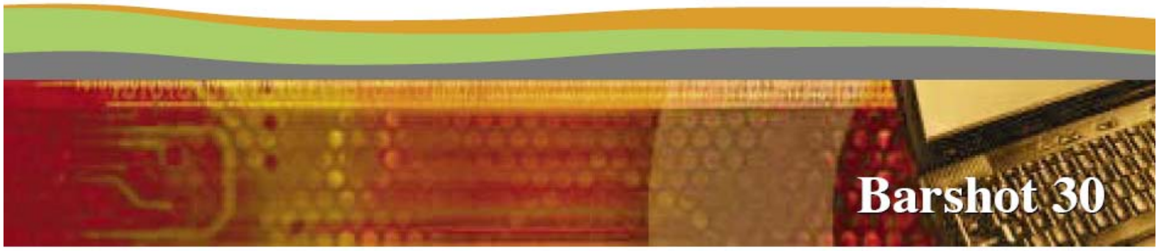


Appendix C

Material Safety Data Sheets

Opta Minerals Inc.

Your one source



Technical Data Sheet

Barshot is produced from the natural mineral "Specular Hematite" (ferric oxide). This is a chemically inert mineral, which cannot rust as the particles are in a fully oxidized form. In addition to producing a low dusting environment, the high level of toughness and hardness makes Barshot an ideal choice in many abrasive applications. Barshot's high specific gravity offers a fast blast rate and low abrasive consumption.

Typical Chemical Analysis (%):

Iron Oxide	Fe_2O_3	~ 98.0
Silicon Dioxide (total)	SiO_2	< 1.0 *
Aluminum Oxide	Al_2O_3	< 1.0
Titanium Oxide	TiO_2	~ 0.1

** Evaluation of Substitute Materials for Silica Sand in Abrasive Blasting (NIOSH, Contract 200-95-2946, Sept. 1998)*

Respirable Silica-Quartz	*None Detected*
Respirable Silica-Cristobalite	*None Detected*

Typical Physical Properties:

Colour:	Lustrous grey / black	**Grain Shape:**	Sub-angular
Bulk Density (loose):	164 lbs./ft.^{3}	**Moh Hardness:**	7
Bulk Density (compacted):	189 lbs./ft.^{3}	**Knoop 100 Hardness:**	~850
Specific Gravity:	~5.4	**Melting Point:**	>1500°C
Moisture:	< 0.20%	**Solubility:**	Insoluble

Air Resources Board: CERTIFIED, 2001

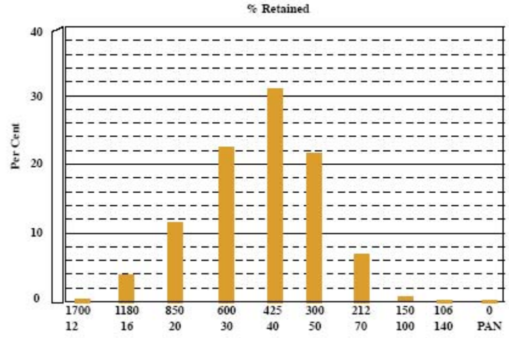
		Result	Specification
California Environmental Protection Agency	% Passing #70 Sieve:	0.1	<1.1
(Test Method No. California 371-A)	5 Micron % (after blast):	0.9	<1.9

Typical Gradation:

Standard 16/50

U.S. Mesh	Microns	Per Cent Retained	Per Cent Passing
12	1700	0.2	99.8
16	1180	4.1	95.7
20	850	11.8	83.9
30	600	23.1	60.9
40	425	31.1	29.8
50	300	21.9	7.9
70	212	7.2	0.7
100	150	0.6	0.1
140	106	0.0	0.0
PAN	0	0.0	0.0

Grain Fineness #:	28.3
Nominal Size (mm):	0.50
Effective Size (mm):	0.32
Uniformity Coeffecient:	1.88



407 Parkside Drive, Waterdown, ON., L0R 2H0 **Tel:** (905) 689-6661 **Toll Free:** 1-888-689-6661 Fax: (905) 689-0485 **E-mail:** info@optaminerals.com **www.optaminerals.com**

Garnet

This MSDS Complies with 29 CFR 1910.1200), Date of Issue: May 1,2002, Revision Date: May 1, 2003

Section 1 - Chemical Product and Company Identification

Product/Chemical Name:	Garnet Abrasive Grains and Powders
Chemical Formula:	$(Fe, Mg)_3\ Al_2(SiO_4)_3$
CAS Number:	1302-62-1
Other designations:	Almandite and Pyrope Garnet
General Use:	Industrial Abrasives
Manufacturer:	Barton Mines Company, L.L.C. 1557 State Route 9, Lake George, NY 12845 Phone: (518) 798-5462 (7:30 AM - 5:30 PM EST) FAX: (518)798-5728 Emergency Phone: (518)798-5462 or (518)251-2296 or (518) 798-5510

Section 2 - Composition / Information on Ingredients

Ingredient Name:	Almandite and Pyrope Garnet (Primary Ingredient)
ACGIH TLV TWA:	10 mg/m^3 Total Dust
CAS Number:	1302-62-1
% Wt.:	94 - 99.6 %
Trace Impurities:	0.4 - 6% misc. trace minerals consisting of Hornblende, Magnetite, and Feldspar.

Section 3 - Physical and Chemical Properties

Physical State:	Solid	**Water Solubility:**	Not Soluble in water
Appearance and Odor:	Red,Pink,Whitish Grains or Powders	**Other Solubilities**:	Not Relevant
Odor Threshold:	No odor	**Boiling Point:**	Not Relevant
Vapor Pressure:	Not Relevant	**Melting Point:**	1,315 ^oC (2,399 ^oF)
Vapor Density (Air = 1):	Not Relevant	**Viscosity:**	Not Relevant
Specific Gravity(H_2O = 1):	3.9 - 4.1	**Mean Refractive Index:**	1.77 - 1.79
pH:	Not Relevant	**Evaporation Rate:**	Not Relevant

Section 4 - Fire Fighting Measures

Flash Point:	Non-flammable solid	**Flash Point Method:**	Not Relevant

LEL: Not Relevant **UEL:** Not Relevant

Flammability Classification: Not Relevant

Extinguishing Media: Use appropriate extinguishing media for surrounding fire.

Unusual Fire or Explosion Hazards: None

Section 5 - Stability and Reactivity

Stability: Stable

Polymerization: Polymerization can not occur.

Chemical Incompatibilities: None known

Hazardous Decomposition Products: None known

Section 6 - Health Hazard Information

Acute Effects (Effects of overexposure)

Inhalation: Dust may cause irritation of nasal and respiratory tract.

Eye: Dust may cause irritation.

Skin: May cause abrasions.

Ingestion: No known effects, however ingestion not recommended.

Medical Conditions Aggravated by Long-Term Exposure:

Chronic respiratory disease may be aggravated by exposure to nuisance dust.

Emergency and First Aid Procedures:

Inhalation: Remove to fresh air, if breathing is difficult, administer oxygen, obtain medical assistance, if needed.

Eye Contact: Flush with large amounts of water, obtain medical assistance, if needed.

Skin Contact: Thoroughly wash exposed area with soap and water.

Ingestion: Obtain first aid or medical assistance, if needed.

Primary route(s) of entry: Inhalation, Skin Contact

Section 7 - Spill, Leak, and Disposal Procedures

Spills: Sweep or vacuum up material for disposal or recovery.

Disposal: Dispose of in accordance with local, state, and federal regulations. Material contaminated in use may require special disposal requirements.

Section 8 - Exposure Controls / Personal Protection

Ventilation: Provide sufficient mechanical (General and/or Local Exhaust) ventilation to maintain dust exposure below threshold limit value (TLV).

Respiratory Protection: If needed use a NIOSH/MSHA approved dust respirator, cartridge, or mask.

Eye Protection: Recommend federally approved safety eyeglasses.

Protective Gloves: As desired by user.

Section 9 - Special Precautions and Comments

No special precautions necessary for normal handling and storage of the material.

The information set forth herein is believed to be accurate but is not warranted with respect to the accuracy of the information or recommendations. Recipients are advised to confirm in advance of need that the information is current and applicable to their circumstances and usage.

Prepared By: R. Strain

METgrit : MATERIAL SAFETY DATA SHEET

Note: The material used in the study was a mixture of shot and grit. This MSDS is typical of this kind of material.

GENERAL INFORMATION

Manufacturer:
Chesapeake Specialty Products, Inc.
5055 North Point Boulevard
Baltimore, MD 21219

Creation Date: November, 1995
Revised Date: August, 2003

For Additional Information, contact:
Occupational Health & Safety Division
(410) 388-5055
Fax: (410) 388-5194 MSDS Code: A181

PRODUCT IDENTIFICATION

Product Name:
METgrit

Formula:
NA

Synonym(s):
Metallic Abrasive

Chemical Family:
Iron

TYPICAL CHEMICAL COMPOSITION (1)

Ingredients*	CAS No.	Wt. %	OSHA PEL	ACGTH TLV
Iron	7439-89-6	Min. 94%	NA	NA

May contain other trace elements such as Calcium Oxide, CAS No. 1305-78-8; Fused Silica Oxide, CAS No. 60676-86-0; Magnesium Oxide, CAS No. 1309-48-4; Aluminum Oxide CAS No. 1344-28-1; Sulfur, CAS No. 7704-34-9; Manganese Oxide, CAS No. 7439-96-5; Potassium Oxide, CAS No. 12136-45-7; Sodium Oxide, CAS No. 12401-86-4; Titanium Oxide, CAS No. 13463-67-7; and Ferric Oxide, CAS No. 1309-37-1

* Since METgrit is manufactured from materials mined from the earth, and process heat is provided by burning fuels derived from the earth, trace but detectable amounts of naturally occurring metals, and possibly harmful elements may be found during chemical analysis. Ingredients are expressed as oxides for quantitative purposes. Actual oxides do not generally occur in "free form" but rather as complexed silica-based glasses or crystals.

PHYSICAL DATA

Physical State:
Solid

Appearance and Odor:
Metallic Gray / Brown Particles
Odorless

Boiling Point:
NA

Melting Point:
NA

Solubility in Water:
NA

pH:
Neutral in water

Specific Gravity
6.8 – 7.4 g/cm3

Vapor Pressure:
NA

Vapor Density:
NA

Evaporation Rate:
NA

% Volatile by Volume:
NA

Particle Size Distribution:
99% of the particles are greater than 100 microns in diameter.

METgrit Chesapeake Specialty Products, Inc.

This product does not meet the criteria of a hazardous chemical as defined by the Federal Occupational Safety and Health Hazard Communication Standard (29 CFR 1910.1200(c). This form is being provided solely as general information and should not be construed as a determination that the product is a hazardous chemical. All sales of this product are subject to CHESAPEAKE'S Standard Terms and Conditions of Sale. CHESAPEAKE MAKES NO WARRANTIES, EXPRESS OR IMPLIED, INCLUDING THE IMPLIED WARRANTY OF MERCHANTABILITY, ANY IMPLIED WARRANTY OF FITNESS FOR A PARTICULAR PURPOSE OR ANY IMPLIED WARRANTIES OTHERWISE ARISING FROM COURSE OF DEALING OR TRADE.

FIRE AND EXPLOSION HAZARD DATA

Flash Point (Method):
NA

Autoiginition Temperature:

Lower Explosive Limit:
NA

Upper Explosive Limit:

NA

NA

Fire Hazard:
NA

Explosive Hazards:
NA

METgrit is non-combustible and not explosive. Therefore there are no flammable or explosive limits nor unusual fire and explosion hazards.

REACTIVITY DATA

Stability:
Stable

Incompatibilities (Materials to avoid):
Strong alkalis and inorganic acids.
Metallic abrasives when wet may react with aluminum powder and other alkali and alkaline earth elements or mineral acids to liberate hydrogen gas. Hydrogen Sulfide gas may be released if the metallic abrasive comes in contact with organic acids. Hydrogen Sulfide is a toxic gas.

Polymerization:
Will not occur

METgrit Chesapeake Specialty Products, Inc.

HEALTH HAZARD DATA

OSHA (Occupational Safety and Health Administration), MSHA (Mine Safety and Health Administration), and ACGIH (American Conference of Governmental Industrial Hygienists), classify the (PEL) Permissible Exposure Limit as 5 mg/m3 for respirable dust and 10 mg/m3 for total dust; for an 8 hour period. Metallic abrasive is not known to cause cancer, however, some people believe crystalline silica can cause cancer. Free titanium oxide has been classified as having limited evidence of causing cancer in animals. Exposure to metallic abrasive dust can affect the skin, the eyes, and mucous membranes.

Acute Exposure:
Powder phase, particularly when in contact with water can dry the skin . The dust can irritate the eyes and upper respiratory system.

Chronic Exposure:
Dust from the powder phase can cause inflammation of the lining tissue of the interior of the nose.

Emergency First Aid Procedures:
Irrigate (flood) eyes immediately and repeatedly with clean water for up to 15 minutes. Get prompt medical attention. Wash exposed skin areas with soap and water. If ingested, consult a physician immediately Drink water.

OCCUPATIONAL EXPOSURE CONTROL MEASURES

Engineering Controls (Ventilation, etc.):
Ventilation should be sufficient to maintain dust levels below the applicable exposure limit for nuisance dust.

Work Practices (Handling and Storage):
Use in such a manner as to avoid creating large amounts of dust.

Eye Protection:

Safety glasses or goggles are recommended when dust levels are excessive.

Skin Protection:
Barrier creams, impervious gloves, boots, and clothing are recommended when dust levels are excessive. Following work with metallic abrasives, workers should shower with soap and water.

Respiratory Protection:
If ventilation does not control exposure levels below the applicable exposure limit for nuisance dust, an OSHA, MSHA, or NIOSH-approved respirator for dusts should be worn.

SPILL, LEAK AND DISPOSAL INFORMATION

Procedures to Follow if Material is Released or Spilled:
If metallic abrasive is spilled, it can be cleaned up using dry methods that do not disperse dust into the air. Avoid breathing the dust. Emergency procedures are not required since there are no hazardous substances in the material as supplied.

Waste Disposal Methods:
Landfill disposal and other methods which are in accordance with local, state and federal regulations. Metallic abrasive can be treated as a common waste for disposal.

METgrit Chesapeake Specialty Products, Inc.

ADDITIONAL OR MISCELLANEOUS INFORMATION

If material is stored in bulk in a closed or confined area, precautions should be observed prior to entering the area. Oxidizing material may deplete the oxygen content of the storage area creating a hazard to entering personnel. If concern arises regarding the safety of entering the area, the oxygen should be checked and, if low, the enclosure should be ventilated until the oxygen level reaches at least 19.5%.

==

Footnotes:
(1) Concentrations may vary somewhat between batches or lots. Where possible, a concentration range is indicated. Occasionally, however, levels may even fall outside of the usual concentration ranges.

(2) Common names, if applicable, appear in parentheses following the chemical names.

(3) All values, unless otherwise specified, refer to 8-hour time-weighted average concentrations and units are in mg/M.

<u>Abbreviations:</u>
NA = Not Applicable
NE = Not Established
UK = Unknown (No applicable information was found)
GT = Greater Than
LT = Less Than

Rust Oleum Safety Yellow Paint

Material Safety Data Sheet

SECTION I - Material Identity

Item Name	
Part Number/Trade Name	RUST-OLEUM SAFETY YELLOW (9906314,0944)
National Stock Number	8010P9906314
CAGE Code	08882
Part Number Indicator	A
MSDS Number	194601
HAZ Code	B

SECTION II - Manufacturer's Information

Manufacturer Name	RUST-OLEUM CORP
Street	11 HAWTHORN PARKWAY
City	VERNON HILLS
State	IL
Country	US
Zip Code	60061
Emergency Phone	800-434-9300 (CHEMTREC)
Information Phone	(847) 367-7700

MSDS Preparer's Information

Date MSDS Prepared/Revised	27APR00
Active Indicator	Y

Alternate Vendors

SECTION III - Physical/Chemical Characteristics

Appearance/Odor	LIQUID WITH SOLVENT ODOR
Boiling Point	318-383 F
Melting Point	NR
Vapor Pressure	ND
Vapor Density	> AIR
Specific Gravity	0.9544
Evaporation Rate	<ETHER< KBD>

Solubility in Water	INSOLUBLE
Chemical pH	ND
Container Type	R
Container Pressure Code	1
Temperature Code	4
Product State Code	L

SECTION IV - Fire and Explosion Hazard Data

Flash Point	104
Flash Point Method	SCC
Lower Explosion Limit	0.6
Upper Explosion Limit	6.5
Extinguishing Media	DRY CHEMICAL, FOAM, WATER FOG
Special Fire Fighting Procedures	WATER MAY BE USED TO COOL CLOSED CONTAINERS TO PREVENT PRESSURE BUILDUP AND POSSIBLE AUTOIGNITION OR EXPLOSION. EVACUATE AREA AND FIGHT FIRE FROM A SAFE DISTANCE
Unusual Fire/Explosion Hazards	KEEP CONTAINERS TIGHTLY CLOSED

SECTION V - Reactivity Data

Stability	YES
Stability Conditions to Avoid	AVOID ALL POSSIBLE SOURCES OF IGNITION
Materials to Avoid	WITH STRONG OXIDIZING AGENTS, STRONG ACIDS & STRONG ALKALIES
Hazardous Decomposition Products	BY OPEN FLAME - CARBON MONOXIDE AND CARBON DIOXIDE
Hazardous Polymerization	NO
Polymerization Conditions to Avoid	WILL NOT OCCUR

SECTION VI - Health Hazard Data

Route of Entry: Skin	YES
Route of Entry: Ingestion	NO
Route of Entry: Inhalation	YES
Health Hazards - Acute and Chronic	CAUSES EYE IRRITATION. VAPORS IRRITATING TO EYES AND RESPIRATORY TRACT. COMBUSTIBLE LIQUID AND VAPOR. HARMFUL IF INHALED. MAY EFFECT THE BRAIN OR NERVOUS SYSTEM CAUSING DIZZINESS, HEADACHE OR NAUSEA
Carcinogenity: NTP	UNK

Carcinogenity: IARC	UNK
Carcinogenity: OSHA	UNK
Explanation of Carcinogenity	NO DATA
Symptoms of Overexposure	[EYE] CAUSES EYE IRRITATION [SKIN] MAY CAUSE SKIN IRRITATION [INHALE] HARMFUL IF INHALED. MAY CAUSE HEADACHES AND DIZZINESS. HIGH VAPOR CONCENTRATIONS ARE IRRITATING TO THE EYES, NOSE, THROAT AND LUNGS. [INGEST] SUBSTANCE MAY BE HARMFUL IF SWALLOWED. ASPIRATION HAZARD IF SWALLOWED. CAN ENTER LUNGS AND CAUSE DAMAGE
Emergency/First Aid Procedures	[EYE] HOLD EYELIDS APART AND FLUSH WITH PLENTY OF WATER FOR AT LEAST 15 MIN. GET MED ATTEN. [SKIN] WASH WITH SOAP AND WATER. GET MED ATTENTION IF IRRITATION DEVELOPS OR PERSISTS. [INHALE] REMOVE TO FRESH AIR. IF NOT BREATHING, GIVE ARTIFICIAL RESPIRATION. IF BREATHING IS DIFFIUCLT, GIVE OXYGEN. GET IMMEDIATE MED ATTEN. [INGEST] ASPIRATION HAZARD. DO NOT INDUCE VOMITING OR GIVE ANYTHING BY MOUTH, THIS MATERIAL CAN ENTER THE LUNGS AND CAUSE SEVERE LUNG DAMAGE. GET IMMEDIATE MED ATTENTION

SECTION VII - Precautions for Safe Handling and Use

Steps if Material Released/Spilled	CONTAIN SPILLED LIQUID WITH SAND OR EARTH. DO NOT USE COMBUSTIBLE MATERIALS SUCH AS SAWDUST. DISPOSE OF ACCORDING TO LOCAL, STATE, AND FEDERAL REGULATIONS. DO NOT INCINERATE CLOSED CONTAINERS
Neutralizing Agent	NR
Waste Disposal Method	DISPOSE OF MATERIAL IN ACCORDANCE TO LOCAL, STATE AND FEDERAL REGULATIONS AND ORDINANCES. DO NOT ALLOW TO ENTER STORM DRAINS OR SEWER SYSTEMS
Handling and Storage Precautions	KEEP CONTAINERS TIGHTLY CLOSED. ISOLATE FROM HEAT, ELECTRICAL EQUIPMENT, SPARKS AND OPEN FLAME. KEEP AWAY FROM HEAT, SPARKS, FLAME AND SOURCES OF IGNITION. KEEP CONTAINER CLOSED WHEN NOT IN USE
Other Precautions	WASH THOROUGHLY AFTER HANDLING. WASH HANDS BEFORE EATING. FOLLOW ALL MSDS AND LABEL PRECAUTIONS EVEN AFTER CONTAINER IS EMPTIED BECAUSE IT MAY

	RETAIN PRODUCT RESIDUES. AVOID BREATHING VAPOR OR MIST. AVOID CONTACT WITH EYES

SECTION VIII - Control Measures

Respiratory Protection	A RESPIRATORY PROTECTION PROGRAM MUST BE FOLLOWED WHEN CONDITIONS WARRANT
Ventilation	LOCAL EXHAUST OR OTHER ENGINEERING CONTROLS TO CONTORL AIRBORNE LEVELS BELOW RECOMMENDED EXPOSURE LIMITS
Protective Gloves	NITRILE OR NEOPRENE GLOVES
Eye Protection	USE SAFETY EYEWEAR DESIGNED TO PROTECT AGAINST SPLASH
Work Hygenic Practices	WASH HANDS AFTER USE
Supplemental Health/Safety Data	NR

SECTION IX - Label Data

Protect Eye	YES
Protect Skin	YES
Protect Respiratory	YES
Chronic Indicator	YES
Contact Code	UNKNOWN
Fire Code	UNKNOWN
Health Code	UNKNOWN
React Code	UNKNOWN
Specific Hazard and Precaution	NONE LISTED

SECTION X - Transportation Data

SECTION XI - Site Specific/Reporting Information

Volatile Organic Compounds (P/G)	3.755
Volatile Organic Compounds (G/L)	449.9948

SECTION XII - Ingredients/Identity Information

Ingredient #	01
Ingredient Name	PETROLEUM DISTILLATES
CAS Number	64742478
Percent	35

Ingredient #	02
Ingredient Name	STODDARD SOLVENT
CAS Number	8052413
Percent	15
OSHA PEL	100 PPM
ACGIH TLV	100 PPM
Ingredient #	03
Ingredient Name	TITANIUM DIOXIDE PIGMENT
CAS Number	13463677
Percent	10
OSHA PEL	15 MG/M3
ACGIH TLV	10 MG/M3
Ingredient #	04
Ingredient Name	MIXED COBALT CARBOXYLATES
CAS Number	1003
Percent	1

Appendix D

Life Cycle Cost Calculations

Unit Costs

Item	Units	Avg., $	Remarks
Barshot	1000 kg	160	
Garnet	1000 kg	275	
Steel Grit / Shot	1000 kg	590	
Labor	hr	25	Labor cost includes, hourly pay rates and benefits
Power	kWh	0.1	Typical energy costs paid by industries in the US
Equipment Depreciation	hr	1.66	A total of $ 10,000 assumed towards blast pot, hoses, secondary air supply unit, and other peripherals; Life of equipment assumed: 4000 hours - 6000 hours
Shrouds	m^2	15	Includes scaffolding, screens, installation labor, and dismantling labor by a contractor; 2 sqft screen required for 1 sqft cleaned; $ 0.75/sqft for screens or $1.50/sqft area cleaned for the entire duration of the blasting work; higher side cost of $1.70/sqft; highly subjective based on work setting.
Cleanup costs	1000 kg	16	
Disposal costs	1000 kg	40	
Emission Fee	1000 kg	8000	

Productivity, Consumption and Emission Evaluation from Developed Models

Abrasive	Pressure (PSI)	Feed Rate	a	b	c	d	e	F	EF (kg/m2)
Barshot	100	4	2.34	0.21	-5.91	-0.001	0.75	0.0025	2.70
Garnet	100	4	-23.28	0.08	11.85	0.0005	-0.9	-0.0466	4.08
Steelgrit/shot	100	4	-2.29	0.08	-1.32	-0.0004	0.18	0.0055	1.51
Abrasive	**Pressure**	**Feed Rate**	**a**	**b**	**c**	**d**	**e**	**f**	**P (m2/hr)**
Barshot	100	4	75.72	-21734.2	416.3	904480	-976.8	9281.25	15.05
Garnet	100	4	-38.85	248.58	412.97	-116587	-855.43	5191.32	14.73
Steelgrit/shot	100	4	-48.12	7743.46	125.32	-423200	-147.13	997.87	11.62
Abrasive	**Pressure**	**Feed Rate**	**a**	**b**	**c**	**d**	**e**	**f**	**C (kg/m2)**
Barshot	100	4	-49.04	41891.61	-1074.41	-1545747	2794.79	-36650.59	29.75
Garnet	100	4	94.5	-5607.64	-351.18	676297	1186.75	-27651.51	23.30
Steelgrit/shot	100	4	209.47	-18944.7	-483.07	1455805	662.07	-14174.3	50.78

Blasting Process Costs Calculations

Variable	Units	Avg. Unit Cost, $	Bar Shot	Garnet	Steel Grit / Shot
Productivity	m^2/hr	NA	15.05	14.73	11.62
Abrasive Consumption	kg/m^2	NA	29.75	23.30	50.78
TPM Emissions	kg/m^2	NA	2.70	4.08	1.51
Abrasive Purchase Cost	$/1000 m^2	From Unit Costs Table	1636.07	1281.58	2792.88
Power Consumption	$/1000 m^2	$ 0.11/ kWh	730.70	746.60	946.35
Labor	$/1000 m^2	$30/ hr	1992.81	2036.17	2580.94
Equipment Capital Cost	$/1000 m^2	$2.08/ hr	138.17	141.17	178.95
Shrouds Cost	$/1000 m^2	$15/ m^2	15000.00	15000.00	15000.00
Used Abrasive Clean-up Costs	$/1000 m^2	$16/ 1000 kg	475.95	372.82	812.47
Used Abrasive Disposal Costs	$/1000 m^2	$40/ 1000 kg	1189.87	932.06	2031.19
Emissions Fee	$/1000 m^2	$8000/ 1000 kg	21600.00	32640.00	12080.00
Total Cost/1000 m^2	**US$**		**42,764**	**53,150**	**36,423**

Vita

Sivaramakrishnan Sangameswaran was born in Chennai, India in 1977. He graduated with an integrated Masters in Biological Sciences and Bachelors in Chemical Engineering from the Birla Institute of Technology and Science, Pilani, India in 1999. He worked for Thermax Ltd as an installation, erection and commissioning engineer of industrial vapor absorption chillers till June 2000. From July 2000 to December 2001, he worked as module leader of Citibank Credit Card authorizations for Polaris Software Labs Ltd, Chennai, India. His areas of interest are air quality monitoring and analysis, industrial risk assessment and hygiene, water quality modeling, bioengineering, stream restoration, storm water modeling and management as well as integrated watershed modeling and management. He is currently employed as an Environmental Engineer with the Bioengineering Group Inc., based in Salem, MA.