Abrasive Blasting Process Optimization: Enhancing Productivity, and Reducing Consumption and Solid/Hazardous Wastes

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ABRASIVE BLASTING PROCESS OPTIMIZATION: ENHANCING PRODUCTIVITY, AND REDUCING CONSUMPTION AND SOLID/ HAZARDOUS WASTES

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ABSTRACT

Abrasive blasting process optimization is aimed at establishing relationships between applied feed rates and resulting productivity and consumption rates. The high waste disposal costs for blasting processes are of increasing concern in shipbuilding industry. Essential care has to be given to all components of the process to enhance productivity and decrease consumption.

This study discusses how the critical parameters, nozzle pressure, and abrasive feed rate affect blasting productivity and consumption rates. These factors subsequently impact the disposal and environmental costs.

Commonly used abrasives were identified and used in this study. The approach adopted consists of a mass balance equation between expended abrasives and disposed wastes on a predetermined area of a plate. The obtained data was analysed to develop productivity and consumption rates for each sample runs. The data was then evaluated to formulate relationships that would enable the derivation of optimum feed rates for desirable productivity and reduced consumption.

1. INTRODUCTION

Abrasive blasting is a widely-used means of surface cleaning and coating removal whose scientific basis has remained essentially crude for over a century. Superior surface preparation is essential in achieving the full life of any coating system. Abrasive blasting is recognized as the most effective means of obtaining such surface profiles. Careful attention to all the components of an abrasive blasting process would elaborate elements that could achieve improved efficiencies in the process.

Abrasive blasting is the process of cleaning the surface with a high velocity jet of abrasive material, which usually is sand, steel shot, garnet, copper slag, coal slag, or lead shot. This process generates a lot of waste both by weight and by volume in the form of used abrasive, old paint and, eroded material. A fraction by weight of used abrasive escapes into the atmosphere too, as particulate matter. The regulations regarding the particulate emissions, hazardous waste and solid waste disposal have changed the general approach of the shipyards towards this process. For blasting, increased productivity results in decreased consumption rates and productivity is governed by many parameters. Such parameters include type of abrasive used, grade of the abrasive, control parameters of the process like the nozzle size, nozzle pressure, nature of the original surface coating, degree of cleaning to be achieved and the desired profile of the specification. Health and Safety Regulations, Standards and Hazards also have a significant impact on the productivity rates depending on the types and amounts of wastes generated.

This report has been made to cover all the basic components of the blasting operations carried out in the shipyard, their requirements and the scope of their better performance in general. However the purpose of this study is to determine the trends and derive equations for productivity rates and abrasive consumption rates for abrasive blasting at different nozzle pressures and feed rates. This project involved a vast amount of literature research published by organizations like the National Shipbuilding Research Program (NSRP), Center for Disease Control and Prevention (CDC), and Institute of Applied Technology (IAT). This study is based on the results from the documented sources of NSRP at 100 psi and testing results conducted at Halter Marine Ship Repair Facility, New Orleans. These tests were conducted to supplement the insufficient data available for research regarding particulate matter generation from dry abrasive blasting. This experiment also generates significant amount of data for predicting equations regarding environmental factors and cost factors.

2. BACKGROUND OF THE STUDY

2.1 Productivity and Consumption Rates

Abrasive productivity is the ratio of the area cleaned to the total elapsed time of the abrasive trial (square feet per hour). The abrasive trial time is defined as the amount of time to clean predetermined area of the panel surface until all of the abrasive media is discharged from the abrasive hopper. The time is measured to the nearest second using a digital stopwatch.

The abrasive consumption rate is calculated as the weight of abrasive used during the trial divided by the measured surface area prepared (pounds per square feet). In the event that the entire amount of abrasive is not discharged during the abrasive trial, the abrasive remaining in the hopper and blast hose is collected and weighed. The amount of abrasive consumed during each trial is calculated by deducting this amount from the initial amount loaded.

2.2 Critical Parameters affecting Blasting Performance

There are many factors that contribute to effective blasting performance. Such factors include proper equipment, optimum process parameters and skilled personnel. Though our focus in this study is the critical process parameters, this section would brief other factors too.

Selection of equipment and size is an important phase. Considerable time has to be dedicated in evaluating the requirements of the operation and components involved in it. For example, the air compressor should be adequate size to suffice the intended needs. Pressure and air volume loss due to hoses and couplings, and the use of the blast machine compressor to supply breathing air for respirators are two other factors that determine the size of compressor. Such needs should be identified and used to determine the size of the air compressor.

Similarly the blast machine should have good abrasive metering capabilities because too little abrasive can give an uneven distribution of particles in the blast pattern. This causes much slower cleaning rates and can leave some surface areas untouched. Excessive abrasive interferes with the abrading action because of abrasive impacting other rebounding particles. The optimum metering adjustment gives a very fine flow of abrasive that can be seen exiting the blast nozzle in a smooth and steady flow. In addition to smooth and easy adjustability, the metering valve should have quick clean-out capabilities when foreign materials cause plugging.

Other equipment includes blast hose, the sole purpose of which is to convey the air-driven abrasive from the blast machine to the blast nozzle. The abrasive/air mixture should flow freely without passing through any undersized hose or fittings that could cause excessive wear and pressure loss. If the blast hose inside diameter (I.D) is decreased by only 1/4 in., the pressure loss can be as great as 12 psi. When the I.D. of hose is doubled, the inner area of the hose is quadrupled. The opposite is true, of course,

when the hose I.D. is reduced. It is important to minimize the length of the blast hose, because this factor also causes pressure loss. In normal operations 4 to 5 psi of pressure is lost due to friction in each 50-foot length of blast hose. Also any coupling that is used on a blast hose should allow a smooth transition between hose lengths of any I.D. The coupling must not interfere with the flow of air and abrasive, and the coupling should only be of the external fitting, quick disconnect style.

In addition to the above mentioned factors following are some abrasives and process parameters that affect blasting performance.

2.2.1 Abrasive

A wide variety of abrasives are available throughout the world, and any of several types may be chosen to accomplish the required surface cleaning.

In the very broadest sense, there are two (2) basic types of blasting abrasives: expendable and re-usable. Sand and slag are two (2) examples of expendable abrasives normally used outdoors. Steel grit and aluminum oxide are two (2) re-usable abrasives normally used in a blast room or blast cabinet where there is some type of reclaim system. Generally speaking, sand and slag are used once and then disposed off; steel grit and other metallic abrasives have a very high re-use factor. Key abrasive properties affecting productivity and consumption rates include:

Friability - Mineral abrasives are more friable than metallic abrasives. This limits their potential for reuse and recycling. Metallic abrasives are always more easily reused than recyclable mineral abrasives. Switching from a traditional expendable mineral abrasive to a recyclable mineral abrasive can reduce consumption rates by 60 - 70%. Switching from a mineral abrasive to a recycled metallic abrasive can reduce consumption rates by 90 - 99%.

Abrasive density - The denser an abrasive the higher the consumption rate (measured in weight used per hour). Abrasive density will not result in a higher volume of abrasive consumption.

Abrasive size - Abrasives with a higher proportion of small particles perform more work than those with a higher proportion of larger particles.

A working mix of abrasive contains a range of particle sizes. Working mixes are created to achieve the desired profile requirements. There is a 30% decrease in the production rate when one goes from a low profile working mix to a medium profile working mix. Going from a medium profile mix to a high profile mix will cause a 50% drop in production rates.

2.2.2 Nozzles

Abrasive blast nozzles with larger openings produce a larger blast pattern on the surface being cleaned. Blast nozzles typically range in size from 1/8 inch to 1/2-inch orifice

diameter, in 1/16 inch increments. Larger sized nozzles also permit more abrasive impacts since more abrasive particles exit the nozzle over a given unit of time. Therefore, productivity increases as a function of the nozzle size. The limiting factor is that larger nozzles require larger volumes of compressed air. Each 1/16 inch increase in nozzle orifice diameter requires approximately twice as much air volume flow for a given blast pressure.

There are currently two types of blast nozzles used in field blasting operations. These are categorized by the nozzle geometry. Straight bore nozzles have a constant orifice diameter for the length of the nozzle. Venturi nozzles converge to the nozzle's size at a point approximately half of the nozzle's length and then diverge for the remainder of the nozzle. The converging portion of the nozzle accelerates the air and abrasive particles resulting in increased impact energy, which in turn, enhances productivity. The diverging portion of the venturi nozzle provides an increase blast pattern.

The pressure of the air/abrasive stream during blasting operations greatly influences the cleaning rates. For most abrasives, increased pressure results in increased productivity rates. Generally, abrasive blasting pressure is increased to the maximum capacity of the air compressor used with the exception of abrasives such as steel grit. Diminishing returns occur at pressures significantly above 100 psi. Some abrasives however, efficiently produce the desired surface cleanliness at lower pressures. Lower pressures impart less energy to the particles, which lowers productivity. Lower pressures permit finer control of cleaning and reduce the breakdown rate of abrasives. Higher nozzle

pressures increase particle energy, cleaning rate and wear of the nozzles and hoses. Higher pressures will also increase operator fatigue, which may result in less productivity over an entire work shift. Increasing pressure at the nozzle by 100% doubles both the production and consumption rate.

2.2.3 Standoff Distance

The standoff distance is the distance that the nozzle is held in relation to the item being cleaned. This distance is critical to abrasive blasting production. Blast operators typically optimize the distance to achieve the desired blast pattern and cleaning rate. This distance could range from 6 inches to 24 inches. Generally, nozzles are held closer to the substrate to clean tightly adherent mill scale or coatings, which require a smaller blast pattern to achieve the specified surface cleanliness. When surfaces being cleaned exhibit loosely adherent coatings or flaking mill scale and rust, the larger blast pattern produced at greater standoff distances allows faster cleaning.

2.2.4 Angle of Attack

The angle of attack is the angle that the nozzle is held to the work-piece. Most field abrasive blast cleaning is performed with the nozzle held between 60° to 120° to the surface. Nozzles held perpendicular (90°) to the surface provide more impact energy, which fractures tightly adherent coatings and mill scale. Nozzles held at angles greater than or less than 90° scour the surface. Experienced abrasive blast operators use a combination to achieve high productivity. Such restrictions, however, can affect cleaning rates.

2.2.5 Dwell Time

Dwell time is the amount of time required to achieve the desired surface cleanliness before the nozzle can be moved to the next area on the substrate. This factor is highly influenced by the size of the blast pattern. For small blast patterns, where the nozzle is held close to the surface being cleaned, the dwell time is very short. When a larger blast pattern is used, the dwell time may be longer. Once again, the operator's skill and knowledge of the cleanliness specification help to reduce dwell time thus increase productivity.

2.2.6 Profile requirements

Generally when shipyard blasting is considered three ranges of profile height are defined. They are:

- Low Profile Range - Between 1.5 and 2.5 mils.
- Medium Profile Range - Between 2.5 and 4.0 mils
- High Profile Range - Over 4.0 mils.

Profile is also important in determining the choice of the abrasive in our decision flow. The selection of profile depth has effects on the choice of abrasive, on its consumption, and on its productivity. First, it steers the user to choose abrasives of appropriate sizes. Second, there are differences in abrasive consumption and productivity from smaller to larger abrasive sizes. The lower the needed profile, the greater the productivity (smaller abrasives are more productive than larger abrasives, more particles doing more work).

Going from a high profile range to a low profile range can triple production rates. The higher the profile, the higher the amount of abrasive consumed for each square foot of cleaning.

2.2.7 Degree of Cleaning

The higher the quality of surface preparation the longer a coating system will provide corrosion protection to a structure or vessel. An SSPC-SP 6 “Commercial Blast Cleaning” specification provides less coating life than an SSPC-SP 10 “Near White Metal Blast Cleaning.” The benefits of SSPC-SP 5 “White Metal Blast Cleaning” over an SSPC-SP 10 cleaned surface are debatable. Changing the degree of cleaning required has a dramatic impact on production rates. Cleaning rates for SSPC-SP 5 are approximately 80 - 90% of those for SSPC-SP 10 cleaning. Production rates double when going from SSPC-SP 10 to SSPC-SP 6 cleaning. There is another doubling in production rate on going from SSPC-SP 6 to SSPC-SP 7 cleaning.

Some of the general types of coating used in the blasting process in shipyards are given below:

> **SSPC-SP 5 (White Metal Blast Cleaning)** - Removal of all mill scale, rust, rust scale, paint or foreign matter by the use of abrasives propelled through nozzles or by centrifugal wheels. A White Metal Blast Cleaned Surface Finish is defined as a surface with a gray-white, uniform metallic color, slightly roughened to form a suitable anchor pattern for coatings. The surface, when viewed without magnification, shall be free of all oil, grease, dirt, visible mill scale, rust, corrosion products, oxides, paint, or any other foreign matter.

SSPC-SP 6 (Commercial Blast Cleaning) - Removal of mill scale, rust, rust scale, paint or foreign matter by the use of abrasives propelled through nozzles or by centrifugal wheels, to the degree specified. A Commercial Blast Cleaned Surface Finish is defined as one from which all oil, grease, dirt, rust scale and foreign matter have been completely removed from the surface and all 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 paint or coating that may remain; if the surface is pitted, slight residues of rust or paint may by found in the bottom of pits; at least two-thirds of each square inch of surface area shall be free of all visible residues and the remainder shall be limited to the light discoloration, slight staining or tight residues as mentioned above.

SSPC-SP 7 (Brush-Off Blast Cleaning) - Removal of loose mill scale, loose rust, and loose paint, to the degree hereafter specified, by the impact of abrasives propelled through nozzles or by centrifugal wheels. It is not intended that the surface shall be free of all mill scale, rust, and paint. The remaining mill scale, rust, and paint should be tight and the surface should be sufficiently abraded to provide good adhesion and bonding of paint. A Brush-Off Blast Cleaned Surface Finish is defined as one from which all oil, grease, dirt, rust scale, loose mill scale, loose rust and loose paint or coatings 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) - Removal of nearly all mill scale, rust, rust scale, paint, or foreign matter by the use of abrasives propelled through nozzles or by centrifugal wheels, to the degree hereafter specified. A Near-White Blast Cleaned Surface Finish is defined as one from which all oil, grease, dirt, mill scale, rust, corrosion products, oxides, paint or other foreign matter have been completely removed from 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. At least 95 percent of each square inch of surface area shall be free of all visible residues, and the remainder shall be limited to the light discoloration mentioned above.

2.2.8 Personnel

Effective blaster training programs are lacking at most yards. There is a need for an effective blaster training program to instruct blast cleaning personnel on how to be more productive through proper use of equipment, air pressure and abrasive. This is because even if all the components of the blasting circuit are efficient to the fullest, it is the ability of the blaster to make use of it and contribute with full efficiency.

3.0 OBJECTIVES OF STUDY

The objectives of this study are as follows:

- To evaluate the optimum pressure and feed rate conditions for increased Productivity and decreased Consumption rates.
- To derive equations establishing relationships between Productivity rates and abrasive feed rates for different abrasives at 80, 100, and 122 psi pressures.
- To derive equations establishing relationships between Consumption rates and abrasive feed rates for different abrasives at 80, 100, and 122 psi pressures.
- To evaluate optimum pressure and feed rate conditions for minimizing solid and hazardous waste generation.
- To identify most environmentally friendly abrasives at 80, 100, and 122 psi pressures and at different feed rates.

4.0 METHODOLOGY

The first step in data collection was to prepare data sets that would enable us to derive the following types of equations for different abrasives:

- Equations to find Productivity at specified feed rates,
- Equations to find Consumption rate at specified feed rates, at constant pressures.

A detailed survey of shipyards and their blasting procedures revealed that the most common abrasives used are Sand, Garnet, Hematite, Coal Slag, and Copper Slag. The survey also identified that the most prevalent blasting pressures ranged between 80 and 120 psi. Based on these results experiments were conducted by the Department of Civil and Environmental Engineering by University of New Orleans in 1999 at Halter Marine Shipyard Facility in New Orleans Area. These experiments were conducted to develop the waste generation rates, and the potential emissions data from the shipyard abrasive blasting operations.

4.1 Data for 80 and 122 psi

The results (Table 4.1 and 4.2) of experiments conducted were used to derive equations for Productivity and Consumption rate at 80 and 122 psi. Attempts were made to obtain maximum blast pressure, with the available compressor, which achieved a maximum of 122 psi. These equations would give the productivity and consumption values at any specified feed rates. Field tests of selected media were conducted at a shipyard located in Louisiana with a test protocol developed based on work previously conducted by

Southwest Research Institute. The test plan and procedure are included in detail in the Appendix A. Blasting was conducted to obtain a Near White finish i.e. SSPC – SP10 surface finish. To validate the precision of sampling techniques and to ensure that valid data is obtained, several quality assurance and quality control techniques were implemented. The American Society for Testing and Materials (ASTM) methods were followed strictly to ensure that the quality of the process is maintained. The closure of the mass balance indicates a significant collection of the spent media.

Table 4.1 Blasting data at 80 psi

Material	Feed Rate (lb/hr)	Feed Rate (Tons/hr)	Productivity (ft^2/hr)	Abrasive Consumption (lbs/ft^2)
Sand	2011.2	0.9	301.8	4.88
Sand	2608.7	1.2	469.8	5.56
Sand	2666.7	1.2	373.3	7.14
Garnet	667.9	0.3	133.6	5.00
Garnet	1049.6	0.5	228.3	4.60
Garnet	1747.6	0.8	349.5	5.00
Garnet	2647.1	1.2	264.7	10.00
Coal Slag	1428.6	0.6	157.1	9.09
Coal Slag	1714.3	0.8	197.1	8.70
Coal Slag	2181.8	1.0	152.7	14.29
Copper Slag	1855.7	0.8	194.8	9.52
Copper Slag	1875.0	0.9	196.9	9.52
Copper Slag	2482.8	1.1	223.4	11.11
Copper Slag	2834.6	1.3	226.8	12.50
Hematite	1406.3	0.6	281.3	5.00
Hematite	1836.7	0.8	303.1	6.06
Hematite	2105.3	1.0	357.6	5.86
Hematite	3000.0	1.4	300.0	10.00

6 Double Venturi Nozzle

Table 4.2 Blasting data at 122psi

Material	Feed Rate (lb/hr)	Feed Rate (Tons/hr)	Productivity (ft^2/hr)	Abrasive Consumption (lbs/ft^2)
Sand	1346.0	0.6	288.6	4.66
Sand	2004.2	0.9	428.4	4.68
Sand	2514.1	1.1	434.4	5.79
Sand	3686.2	1.7	430.8	8.56
Garnet	1486.1	0.7	319.2	4.65
Garnet	1623.4	0.7	436.8	3.72
Garnet	3165.0	1.4	450.0	7.03
Garnet	3780.4	1.7	412.8	9.16
Coal Slag	2590.2	1.2	426.0	6.08
Coal Slag	2889.6	1.3	613.2	4.71
Coal Slag	3233.2	1.5	528.6	6.12
Copper Slag	2590.2	1.2	426.0	6.08
Copper Slag	2889.6	1.3	613.2	4.71
Copper Slag	3233.2	1.5	528.6	6.12
Hematite	2843.8	1.3	375.0	7.58
Hematite	3195.7	1.5	478.2	6.68
Hematite	3686.3	1.7	443.4	8.32

6 Bazooka Nozzle

4.2 Data for 100 psi

The data for the 100 psi blasting pressure is obtained from the NSRP documents. The set of data provided by the NSRP documents are the results from studies conducted to demonstrate the effects of abrasive recycling, elevated nozzle pressures, abrasive metering, nozzle wear, abrasive quality, blaster training, original surface conditions, the hardness of the coatings, the profile of the substrate, and the degree of cleaning to be achieved on the productivity and consumption rates.

The abrasives considered in the literature were mainly classified into mineral and metallic materials. The data found was for the abrasives Coal Slag, Star Blast, Aluminum Oxide, Steel Grit and Garnet.

The developed procedure used to obtain this data is outlined as follows: The procedure starts by taking a known weight of abrasive. This known quantity of abrasive sample is placed in a 300 lb blast pot fitted with a metering valve. The surface to be blast cleaned should then be scribed into 1 square foot segments for ease in measuring the total area blast cleaned. The meter valve is then closed and then meter valve is opened to 2 turns. A minimum 100 psi air pressure at the nozzle is used. The time to blast clean a measured area using the entire abrasive charge is recorded. Blasting is done to a standard degree of cleanliness, i.e. SSPC SP 5. The preceding procedure is repeated using the same weight of abrasive, at metering valve settings of 3 turns and 4 turns. Comparison of the productivity (square feet per minute blast cleaned) Vs abrasive consumption (pounds abrasive per square foot blast cleaned) at the three different metering valve settings (2,3 and 4 turns) and fine tune with 1/2 turns will achieve optimum setting.

Using the abrasive metering test procedure outlined above, a series of abrasive evaluations tests were performed to establish how various abrasive types affect metering valve settings. These results are shown in Table 4.3. The results show that small changes in metering valve turns can produce large changes in abrasive consumption. It is also evident that there is no single metering valve setting that fits all abrasives because abrasive metering is affected by particle shape, size, and density as well as nozzle

pressure. This reiterates the discussion in the second chapter regarding the affect of meter settings on productivity and consumption rates.

Table 4.3 Blasting data at 100psi

Abrasive type	Feed Rate lb/min	Feed Rate Tons/hr	Productivity sq. ft/hr	Consumption lb/sq.ft
Coal Slag	16.8	2.2	338.0	3.00
Coal Slag	21.0	2.8	360.0	3.50
Coal Slag	27.6	3.6	256.0	6.50
Star Blast	12.0	1.6	270.0	2.70
Star Blast	30.6	4.0	412.0	4.40
Star Blast	38.4	5.1	400.0	5.80
Aluminium Oxide	14.1	1.9	129.0	6.50
Aluminium Oxide	28.5	3.8	216.0	7.90
Aluminium Oxide	70.2	9.3	338.0	12.40
Steel Grit	11.8	1.6	126.0	5.60
Steel Grit	30.2	4.0	222.0	8.20
Steel Grit	38.0	5.0	213.0	10.70
Steel Grit	43.3	5.7	219.0	11.80
Garnet	5.7	0.8	73.0	4.70
Garnet	12.3	1.6	218.0	3.40
Garnet	22.1	2.9	232.0	5.70
Garnet	23.4	3.1	234.0	6.10
Garnet	46.7	6.2	263.0	10.70
Glass Blast	16.8	2.2	215.0	4.70
Glass Blast	21.9	2.9	250.0	5.30
Glass Blast	25.2	3.3	333.0	4.50
Glass Blast	39.7	5.2	333.0	7.20

8 Bazooka nozzle

The data sets obtained for the mentioned pressures was used to derive equations useful in estimating the productivity rates and consumption rates for the blasting process in controlled environment. Controlled environment, implies that the cleaning process is administered under known measures of pressures, nozzle sizes and other parameters.

5.0 RESULTS AND DISCUSSION

The data obtained provides an opportunity to evaluate the productivity, and consumption rates at different feed rates and pressure. Efficiency is always obtaining maximum output from minimum input. The productivity of abrasive blasting process depends on the input (feed rate) and also on the control parameters like pressure. The discussion here would attempt to evaluate dependence of productivity and consumption rates on both of these components with an ultimate objective to reduce the burden of excessive multimedia wastes and associated disposal costs.

5.1 Productivity Trends

The data sets developed in Tables 4.1 were used to develop graphs to study the productivity trends of sand, garnet, coal slag and hematite at 80 psi. nozzle pressure with feed rates on X axis with units of tons/hr and productivity on Y axis with units sq.feet/hr as shown in the graphs 1 – 5. It is observed from the graphs that productivity rate for most abrasives increases with increase in feed rate up to certain level after which it reduces. This trend indicates that productivity reaches its highest limit at a fixed pressure and with any further increase in feed rate there is only decrease in productivity. It is also observed from the graphs that sand among the mentioned abrasives offers highest productivity rates. And copper slag exhibits a steep increase in productivity with a small increase in feed rate until it reaches the maximum productivity.

Similar graphs were developed to study the abrasive's coal slag, star blast, aluminum oxide, steel grit, and garnet at 100 psi nozzle pressure. Data for these abrasives is obtained from data sets developed as shown in Table 4.3. Graphs 5 – 10 illustrate the trends followed by productivity curves. The composition of steel grit is mainly composed of iron and can be considered as a variation of hematite. Star blast has a composition of Staurolite (Iron Aluminum Silicate Hydroxide). It is observed that at 100 psi. pressure also productivity trends have shown an increase with increasing feed rates until a certain limit after which productivity decreases with increase in feed rate.

Similar trends have been observed for sand, garnet, coal slag and hematite at 122 psi nozzle pressure as shown in the graphs 10 – 15.

5.2 Consumption Trends

Contrary to the productivity trends, graphs developed for consumption rates show a decrease with increase in productivity up to a certain level after which the consumption rates increase with any increase in feed rate. The graphs 1- 5 show such trends developed at 80 psi. pressure for the mentioned abrasives. Graphs 6 – 10 for 100 psi pressure and 11 – 15 for 122 psi pressures also indicate similar trends.

5.3 Mathematical Model

The graphs mentioned in the above sections for productivity and consumption rates were used to develop mathematical model of equations. These equations were developed using a mathematical procedure for finding the best-fitting curve to the given set of points by minimizing the sum of the squares of the offsets ("the residuals") o f the points from the

curve. Table 5.1 summarizes the equations for different abrasives at 80, 100, and 122 psi pressures.

5.4 Environmental friendly abrasives

As mentioned in the beginning of this section, most efficient or productive abrasives exhibit lower consumption rates. The productivity and consumption rate data for all the abrasives used for 80 psi were plotted as shown in Graph 16 and 17. Similar graphs were developed for 100 and 122 psi nozzles pressures and shown in graphs 18-21. These graphs were developed to compare abrasives and their behavior is summarized in Table 5.2. Table 5.2 provides the variation of productivity and consumption rates for different abrasives in some specified feed rate ranges. As you move from the left column to right column productivity decreases and consumption rate increases in a feed rate range. For example, it is observed for 80 psi pressure that garnet exhibits highest productivity and lowest consumption rates for feed rate ranges 0.6 through 1 ton/hr. In the same pressure scenario, coal slag exhibits low productivity and high consumption rates for feed rate ranges from 0.8 through 1.2 tons/hr.

5.4.1 Reduced Solid and Hazardous Wastes

In light of stringent waste management regulations and heightened awareness of environmental contamination, additional focus has been placed on appropriate management of the blasting wastes. Blasting wastes can be hazardous due to high concentrations of metals, such as lead, chromium, zinc, and cadmium, or organics.

As with any non-excluded solid waste, the generator of the waste is responsible for determining if the waste possesses hazardous characteristics, it is a necessary step in

determining the disposal and reuse options available. Environmental regulations require that a Toxicity Characteristic Leaching Procedure (TCLP) test be performed to determine if the material is hazardous. If it is hazardous, the material must be managed accordingly. If not determined hazardous, the wastes are solid wastes which must be disposed of properly in prescribed landfills.

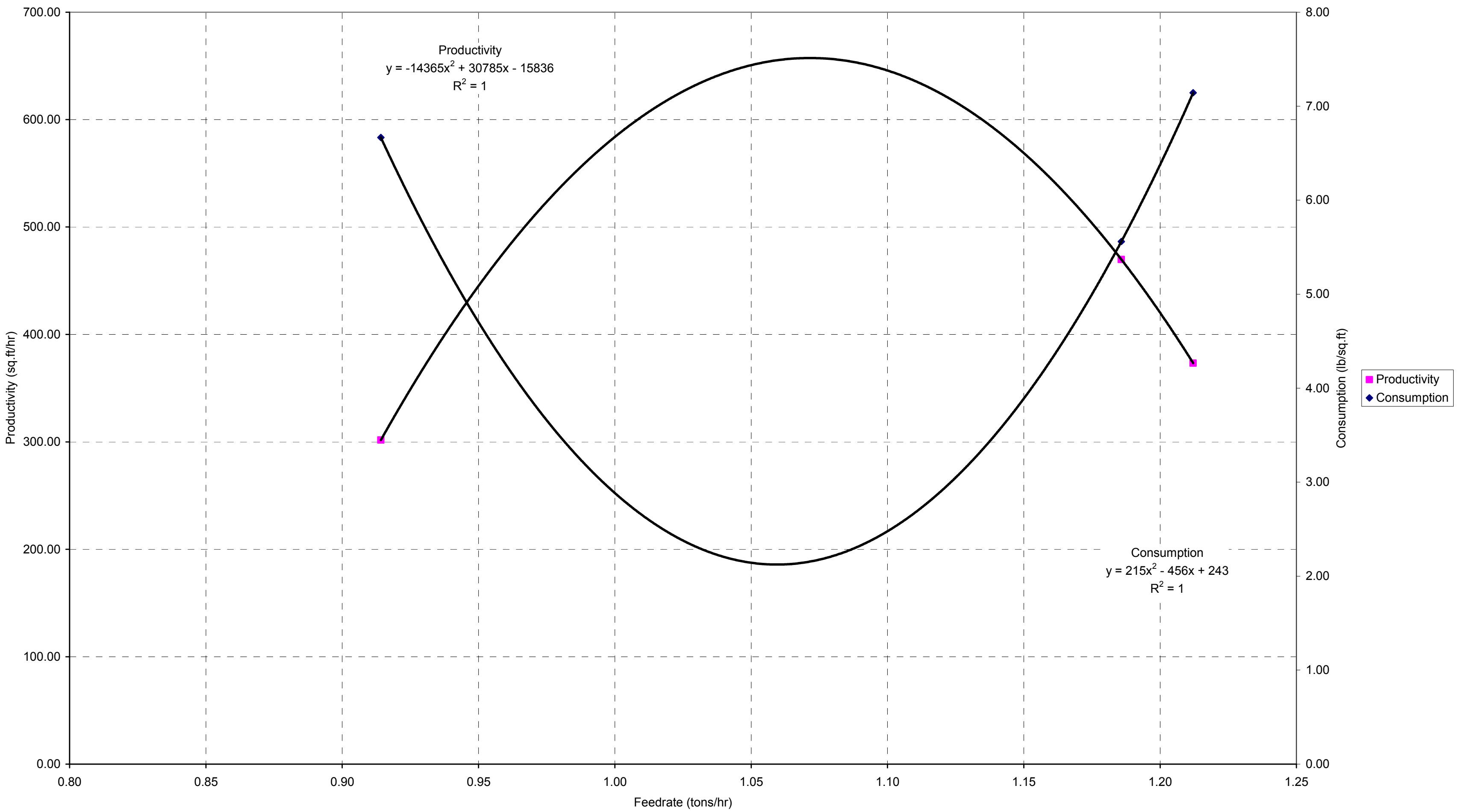
The challenges of classifying, transporting, storing, and finally disposing or remediating to applicable standards under environmental regulations are reduced to a large extent by use of environmentally friendly abrasives. The associated costs are also reduced.

5.4.2 Miscellaneous Benefits

Other benefits with increased productivity and reduced consumption by use of environmentally friendly abrasives include:

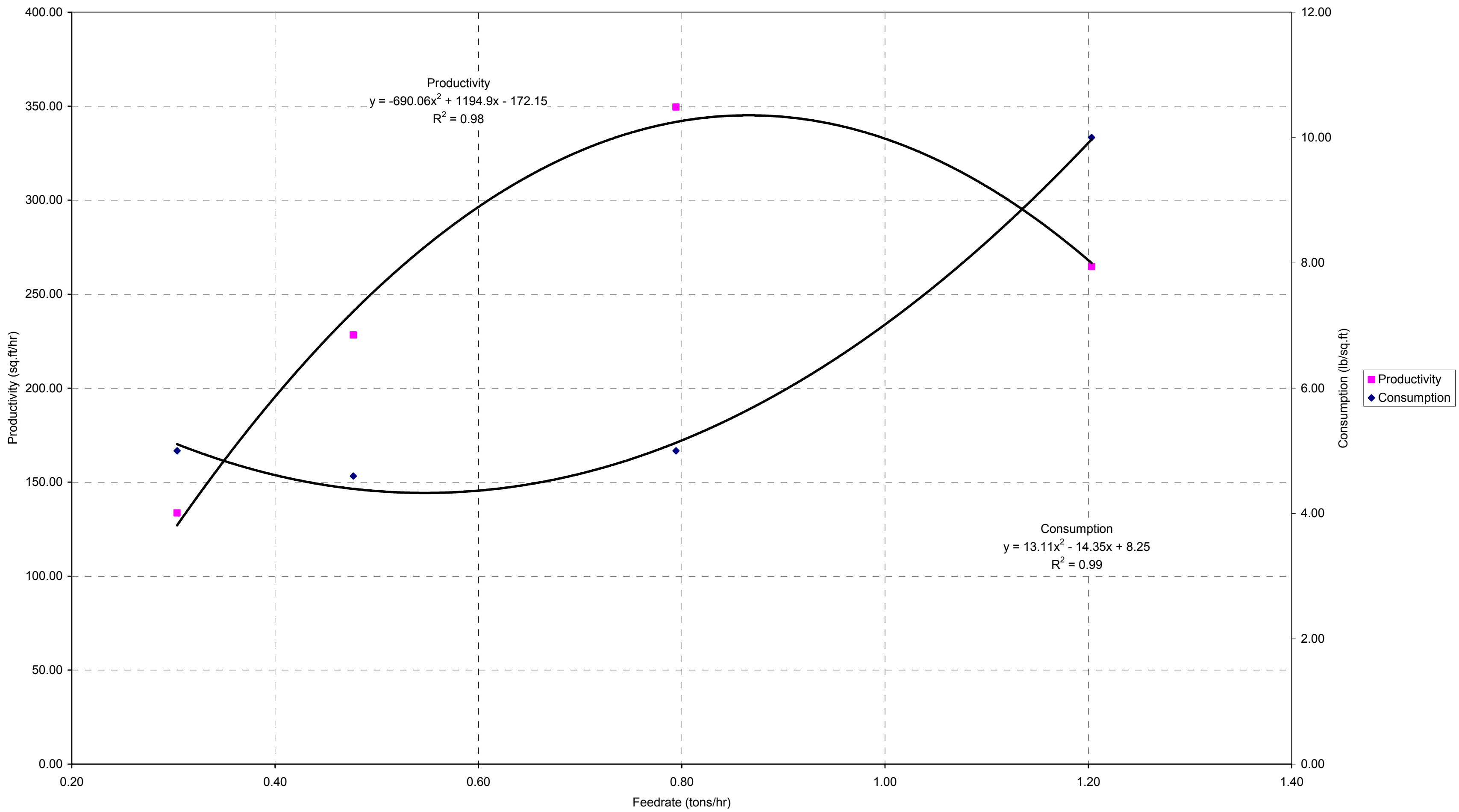
- Reduced energy costs;
- Reduced life-cycle costs on equipment;
- Attractive return on investment; and
- Improved economics for enhancing environmental quality.

Graph 1. Sand at 80 psi.



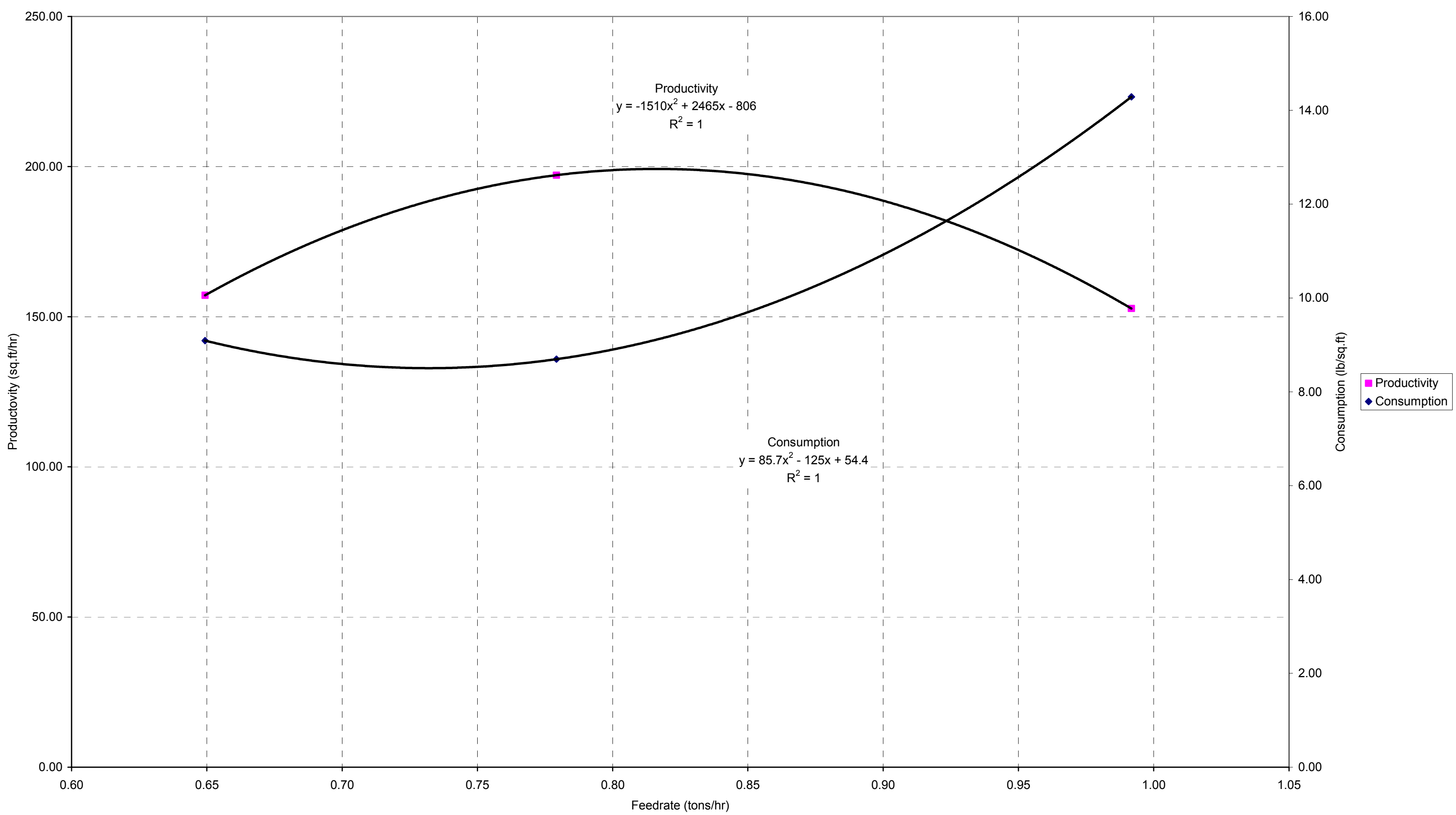
6 Double Venturi Nozzle

Graph 2. Garnet at 80 psi.



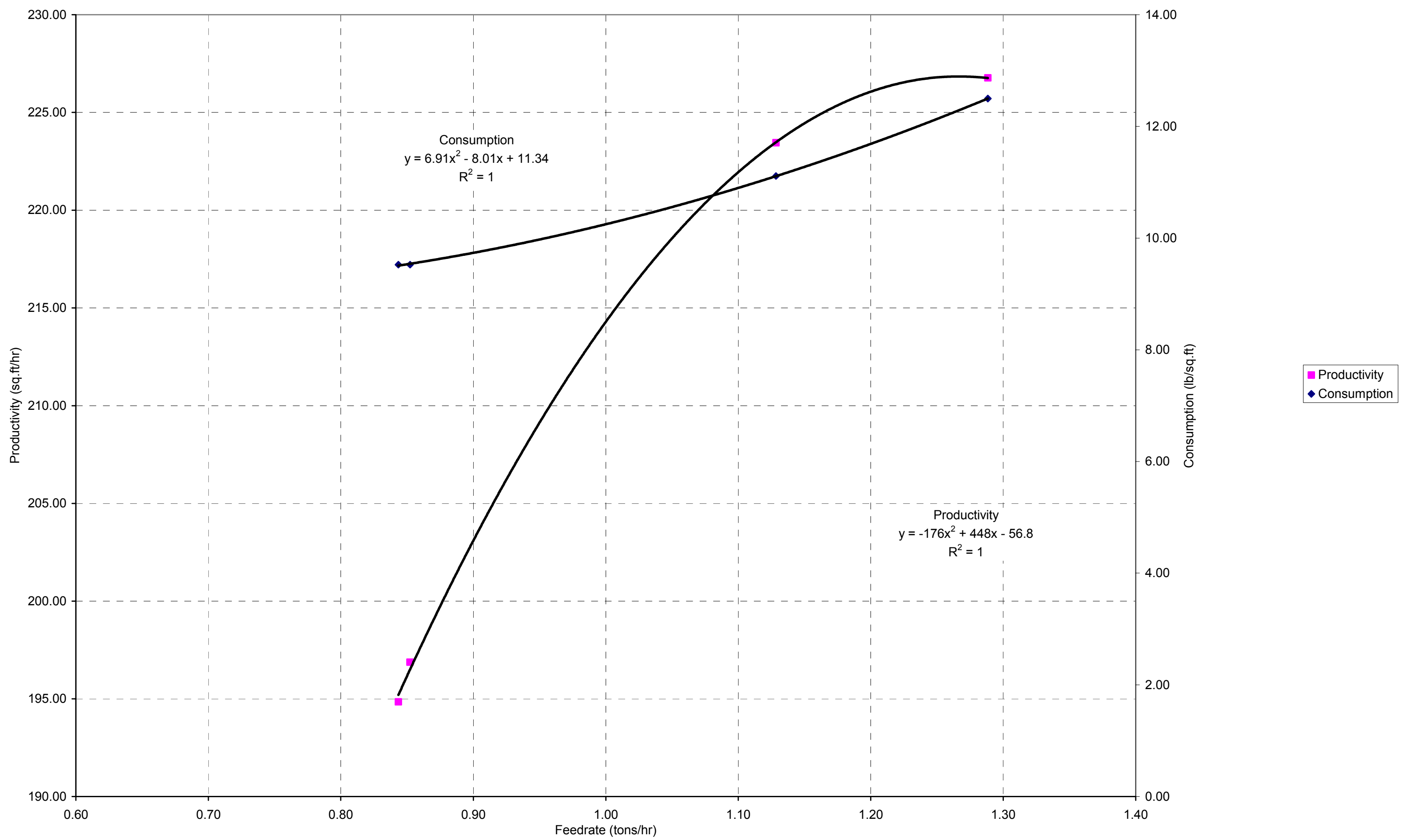
6 Double Venturi Nozzle

Graph 3. Coal Slag at 80 psi.



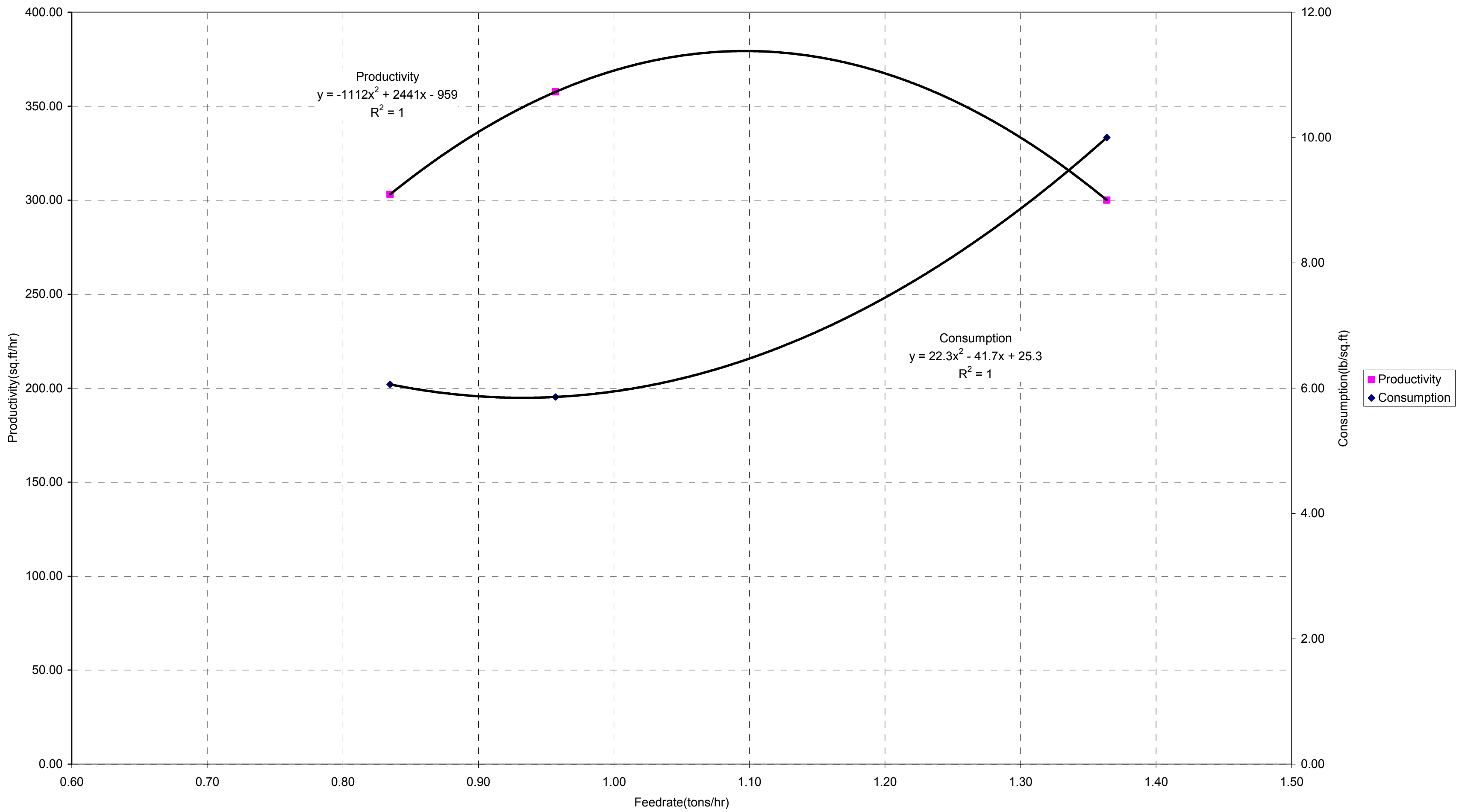
6 Double Venturi Nozzle

Graph 4. Copper Slag at 80 psi



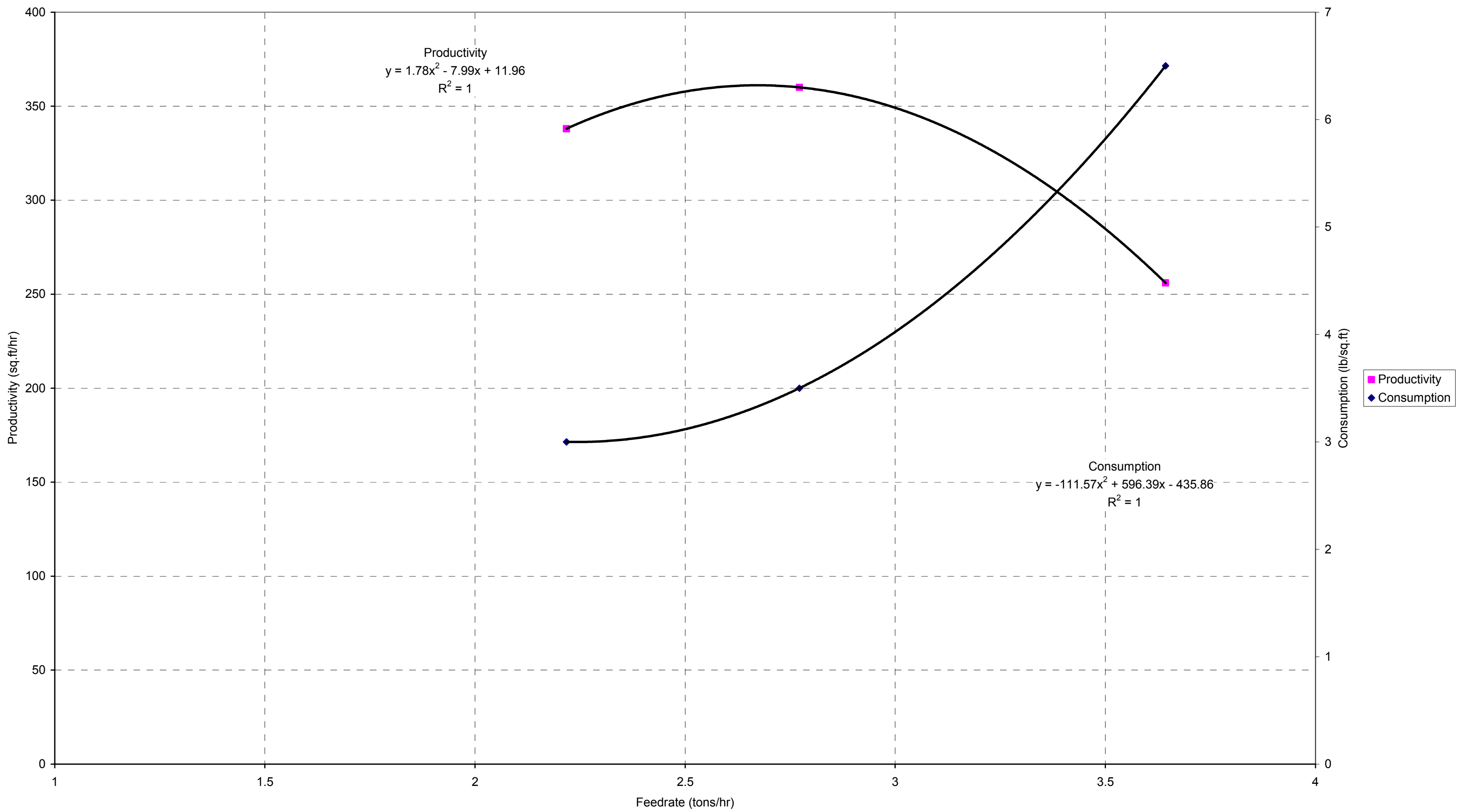
6 Double Venturi Nozzle

Graph 5. Hematite at 80 psi.



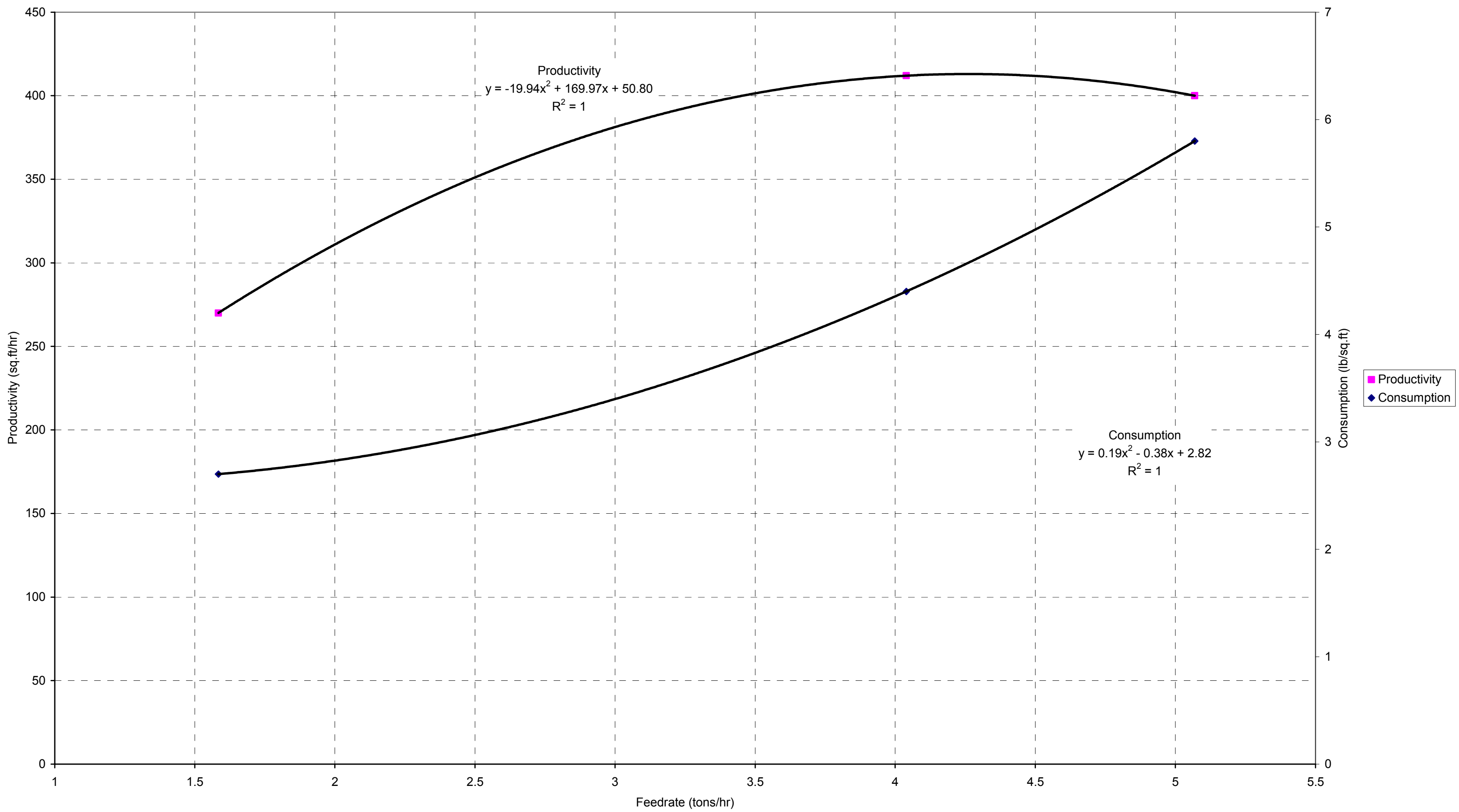
6 Double Venturi Nozzle

Graph 6. Coal Slag at 100 psi.

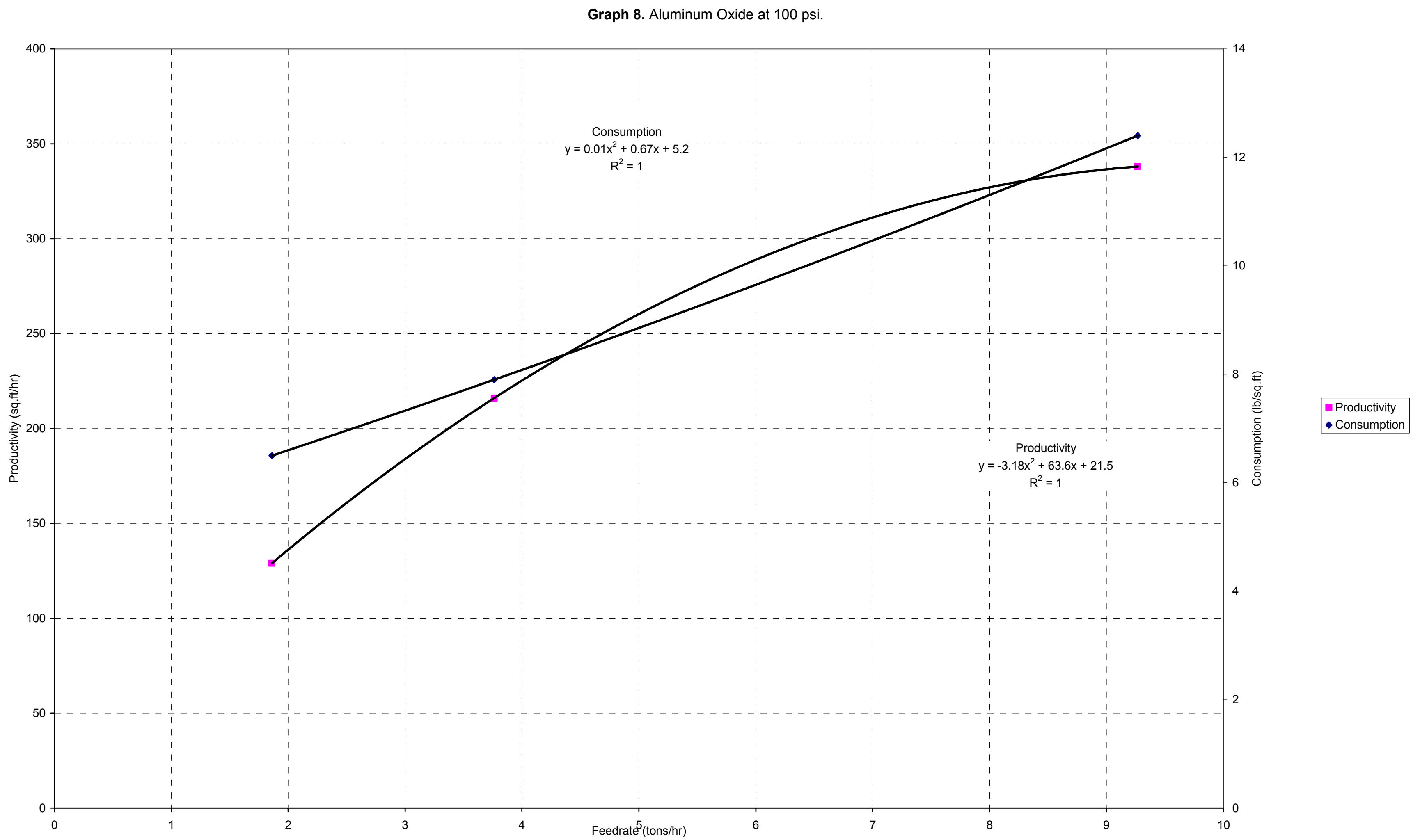


8 Bazooka Nozzle

Graph 7. Star Blast at 100psi.

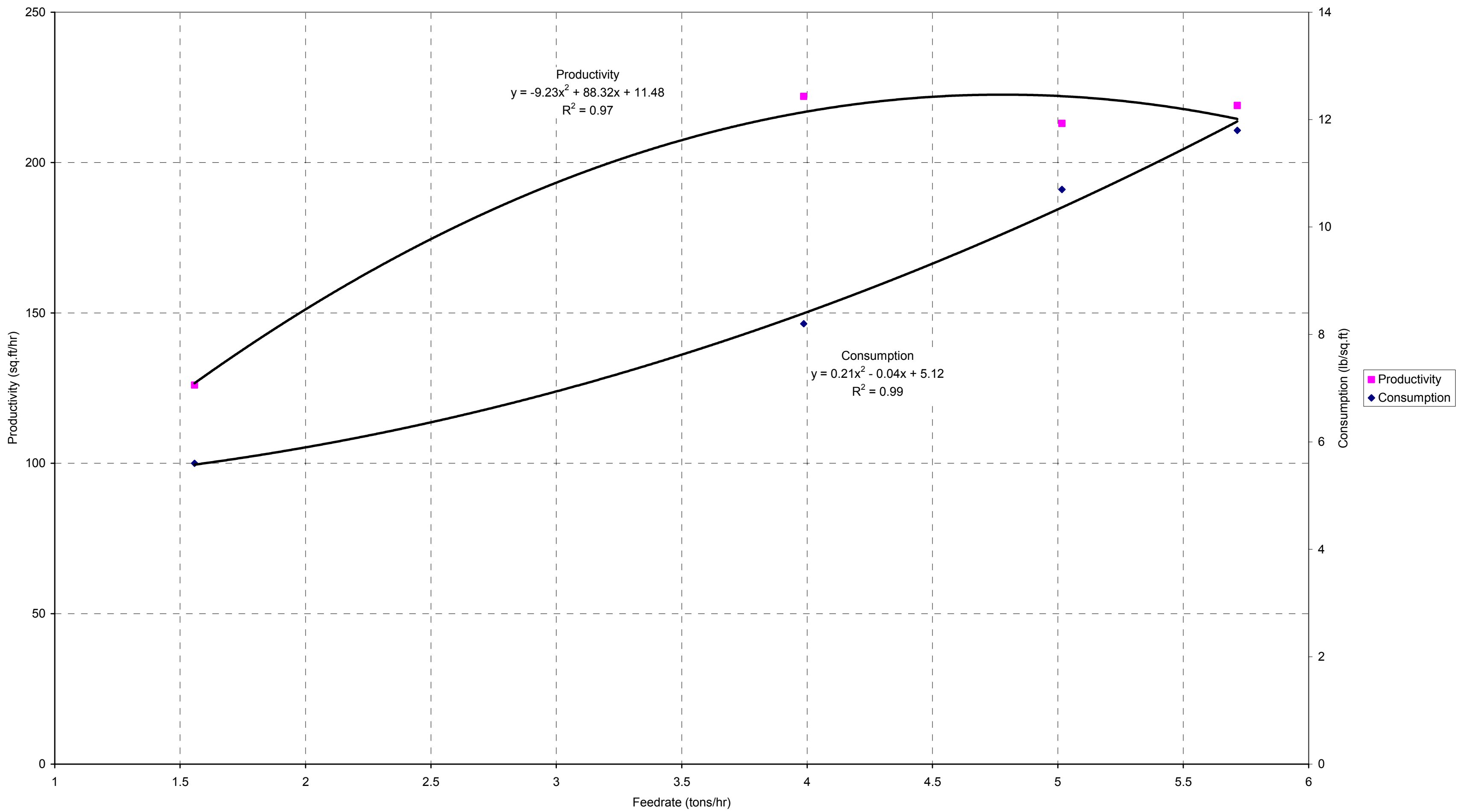


8 Bazooka Nozzle



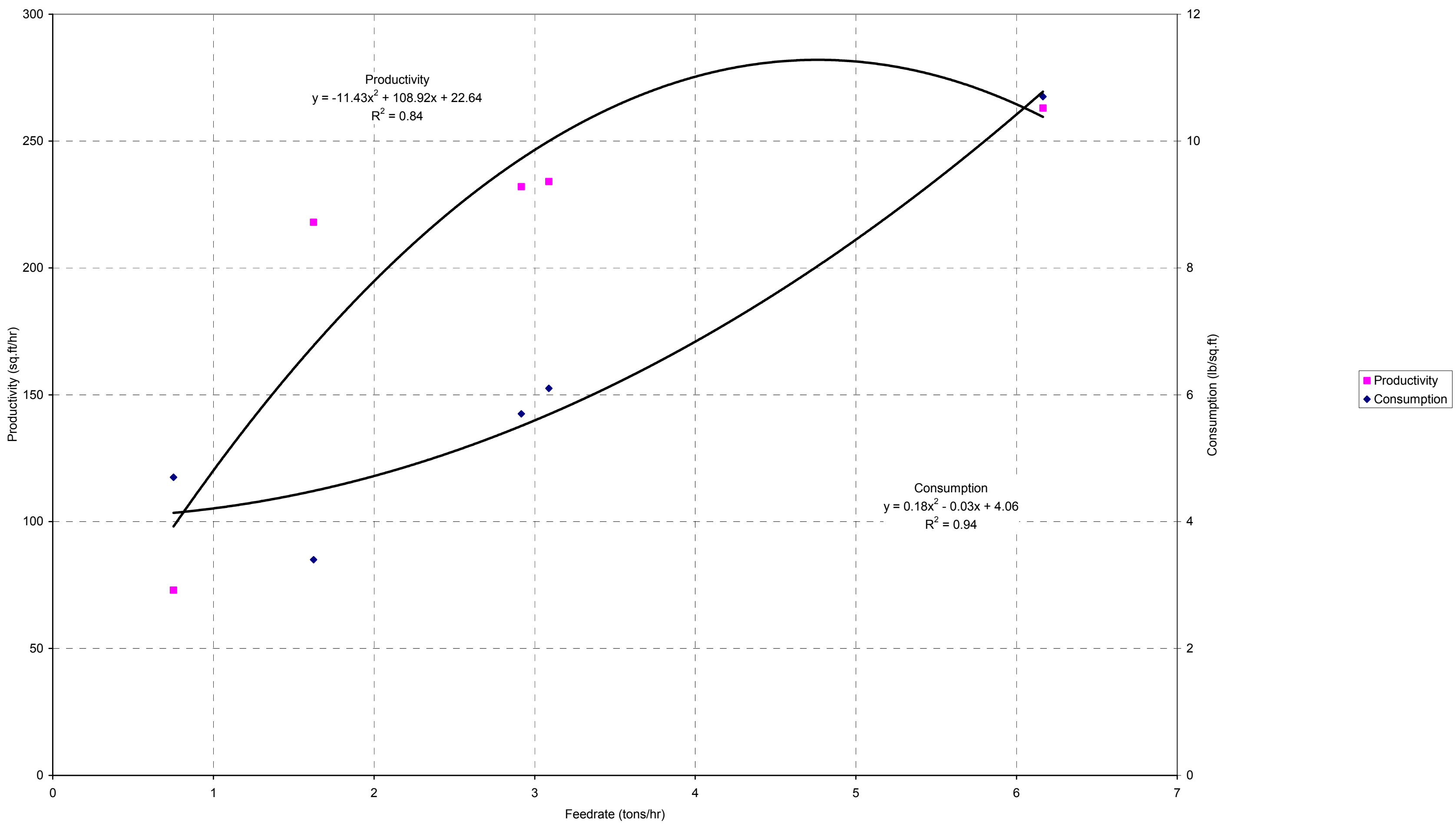
8 Bazooka Nozzle

Graph 9. Steel Grit at 100 psi.



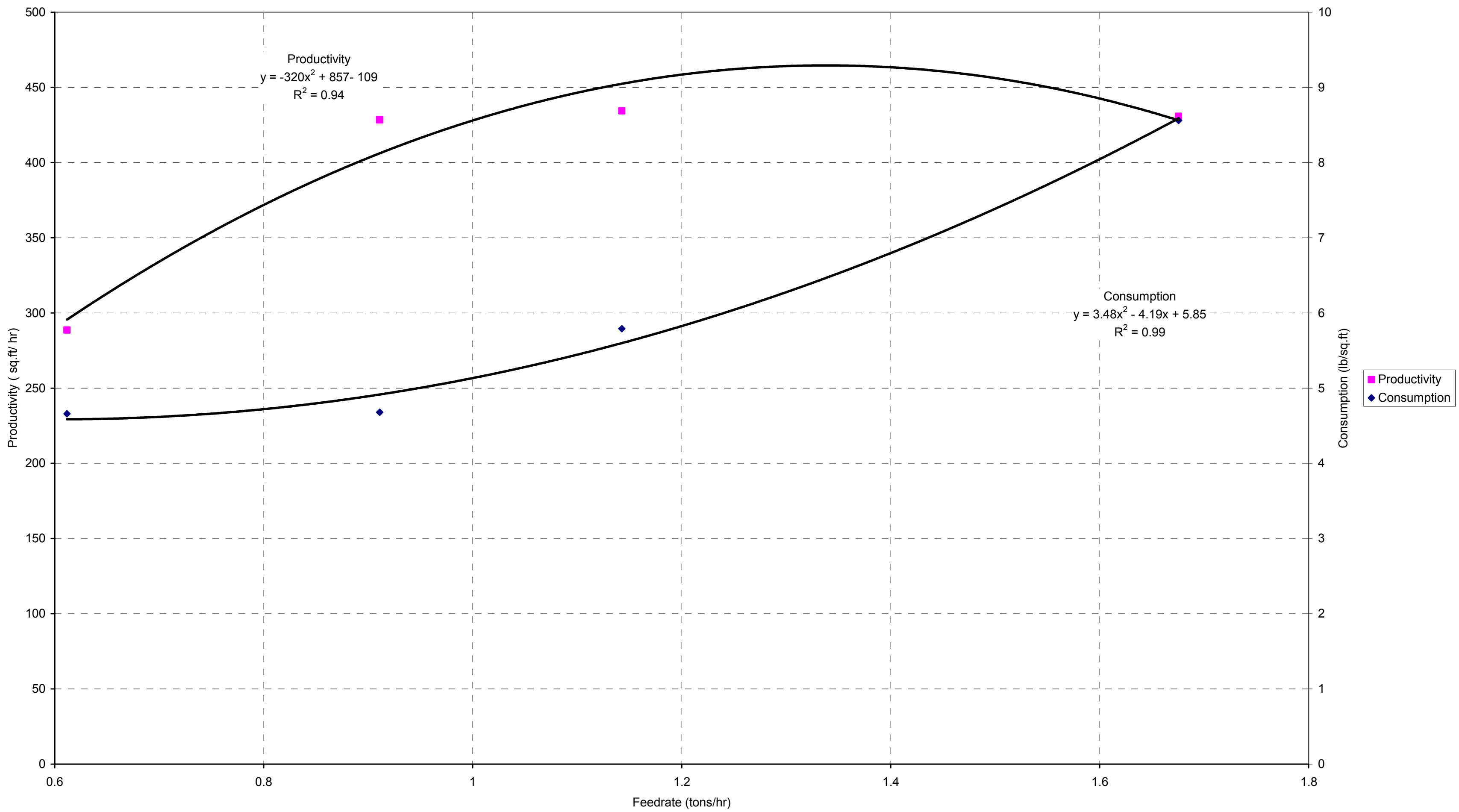
8 Bazooka Nozzle

Graph 10. Garnet at 100 psi.



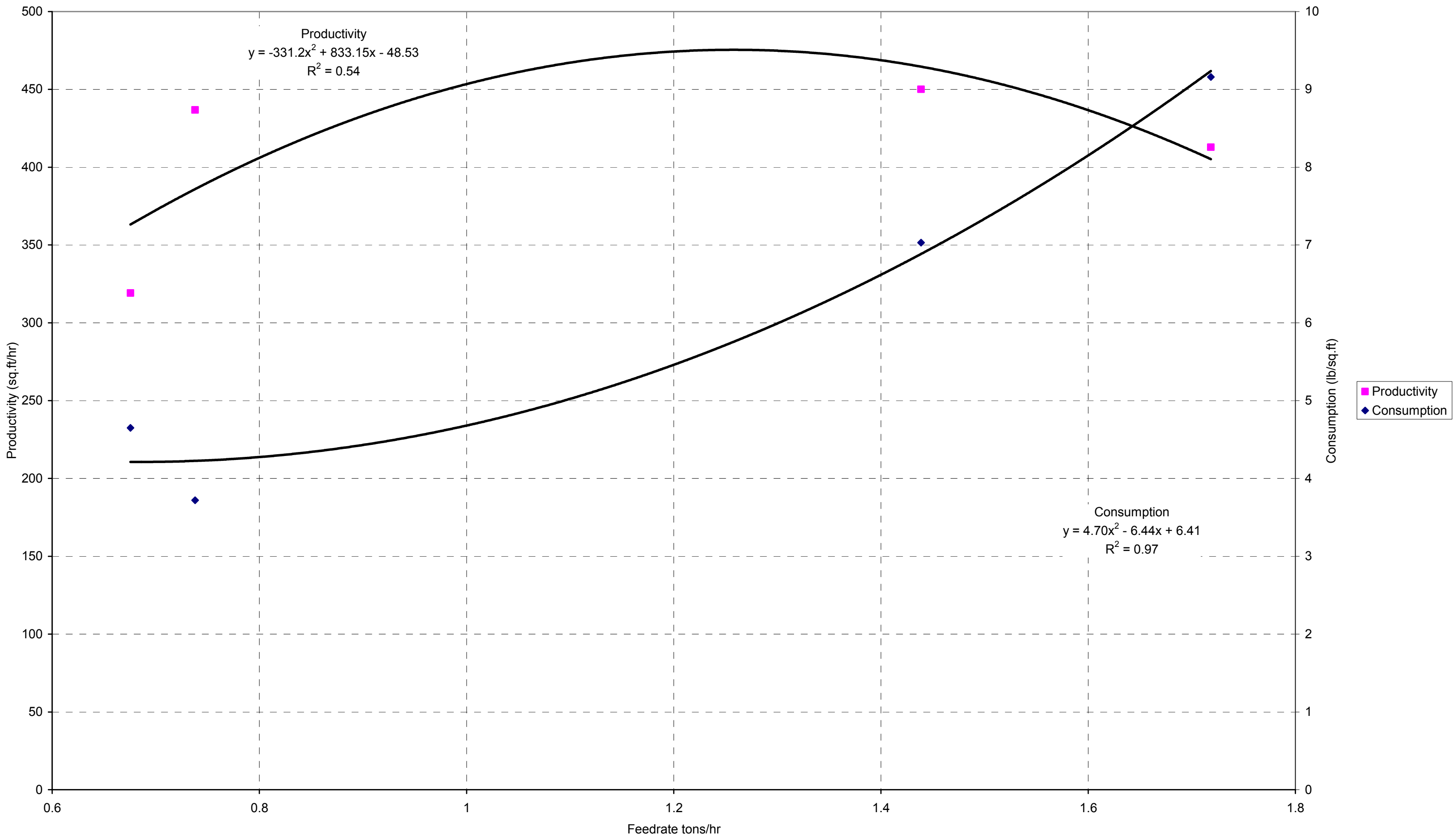
8 Bazooka Nozzle

Graph 11. Sand at 122 psi.



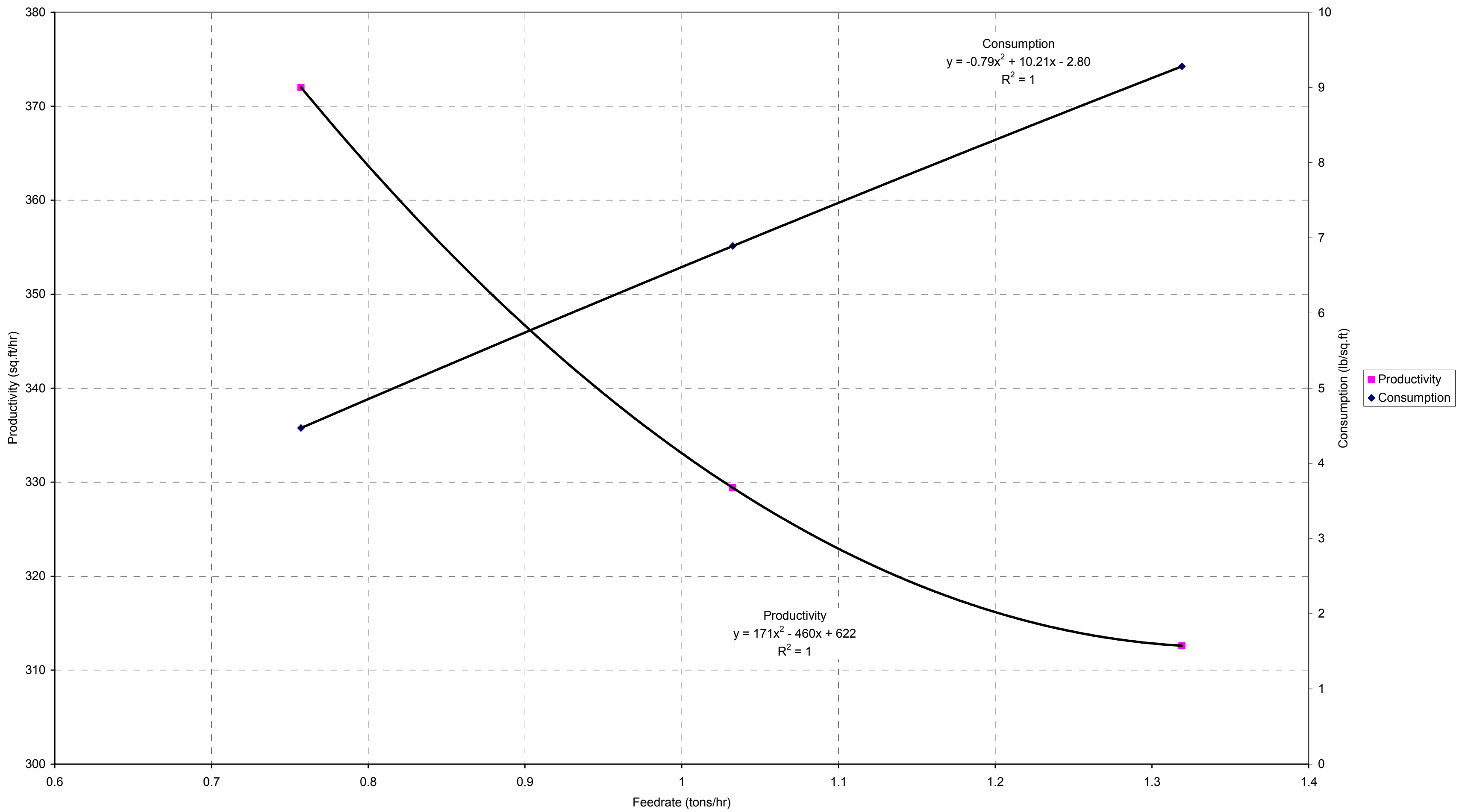
6 Bazooka Nozzle

Graph 12. Garnet at 122 psi.



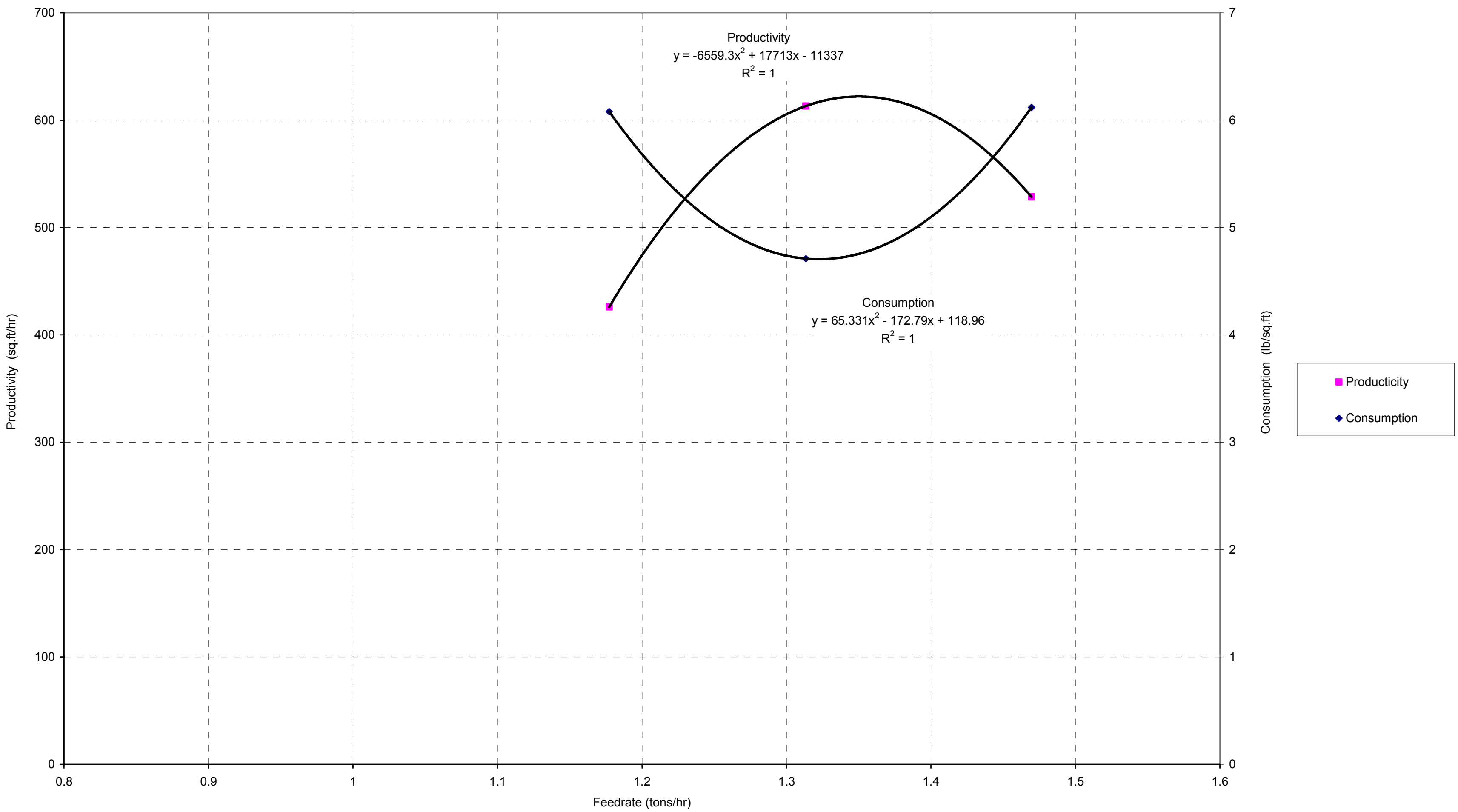
6 Bazooka Nozzle

Graph 13. Coal Slag at 122 psi.



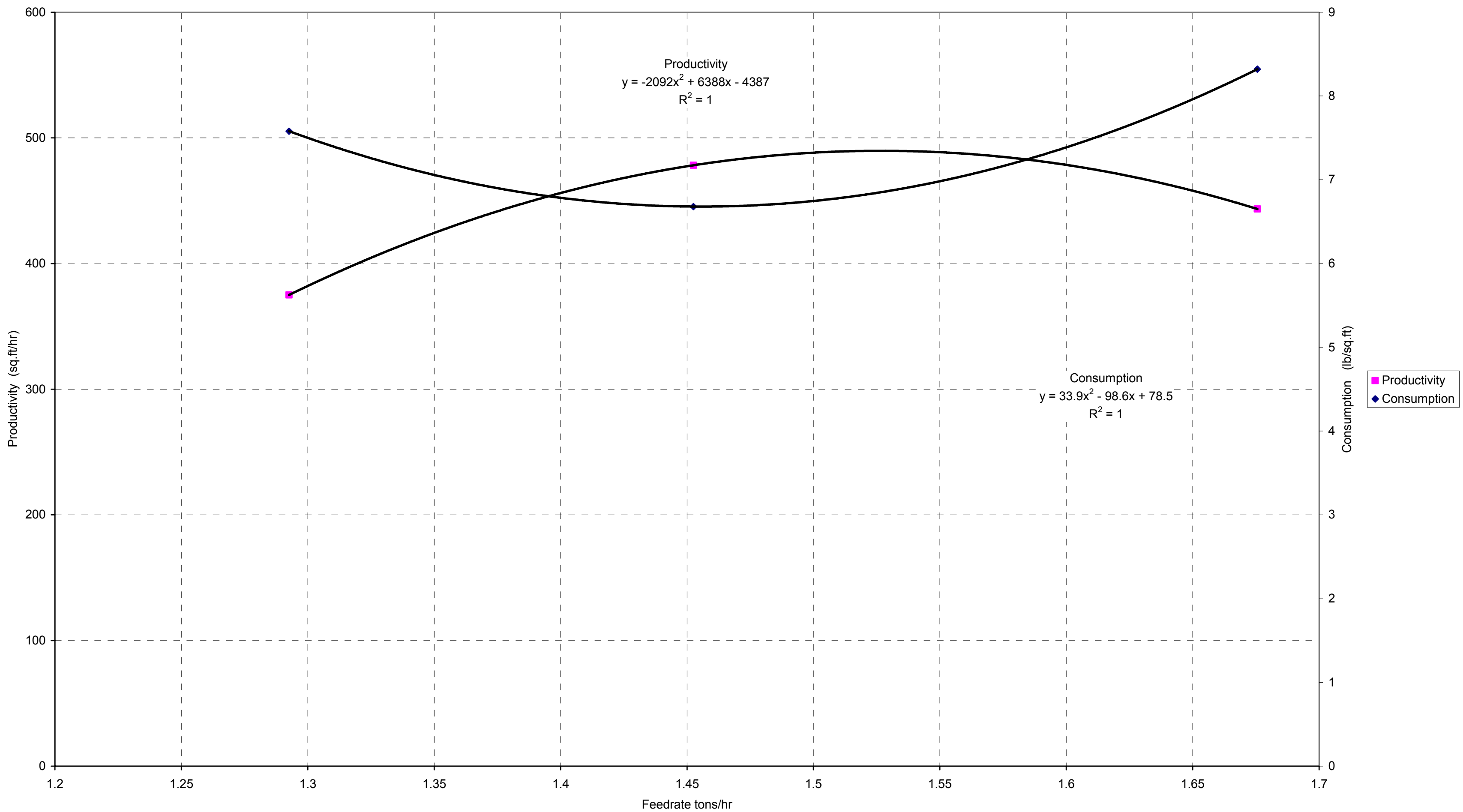
6 Bazooka Nozzle

Graph 14. Copper slag at 122 psi.



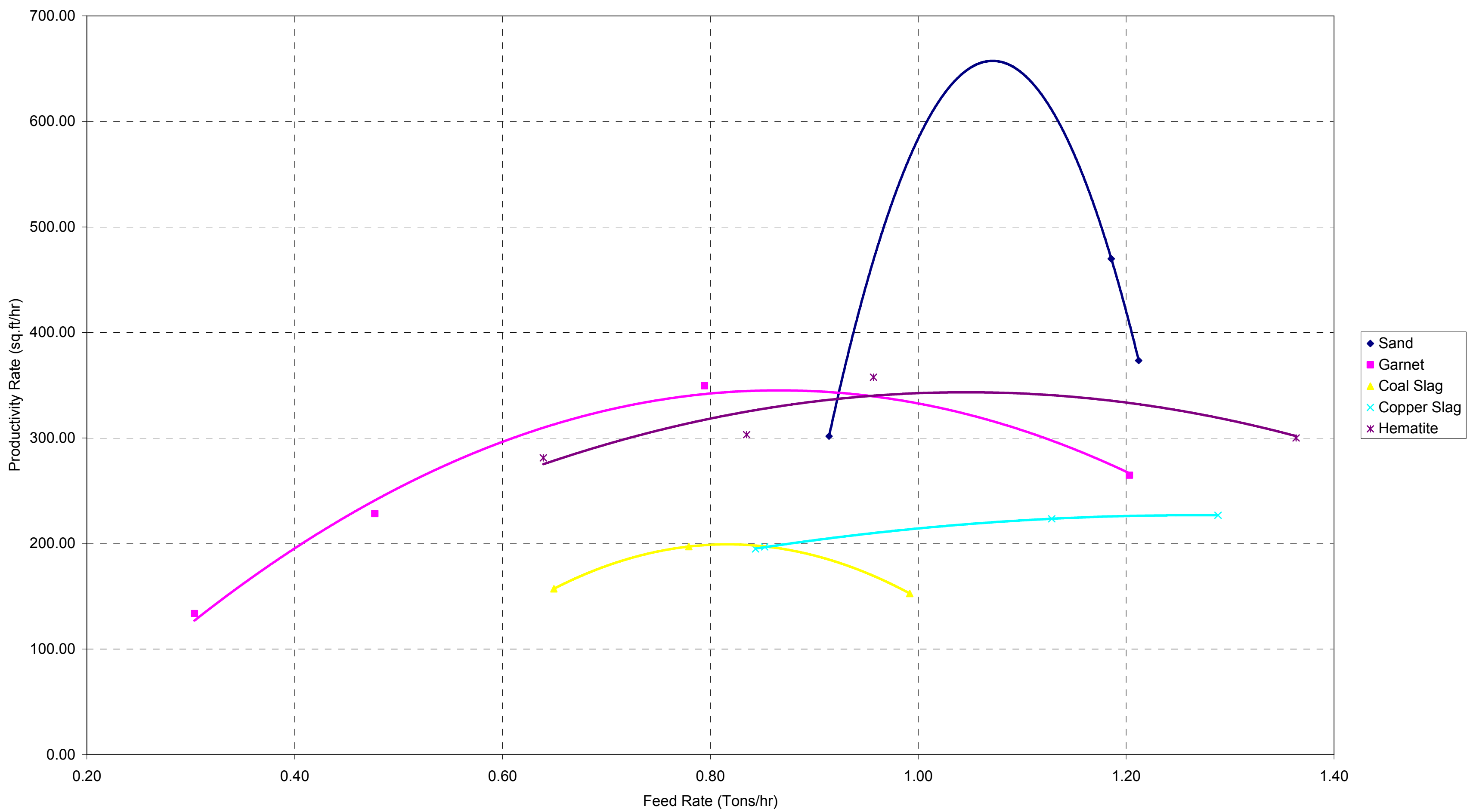
6 Bazooka Nozzle

Graph 15. Hematite at 122 psi.



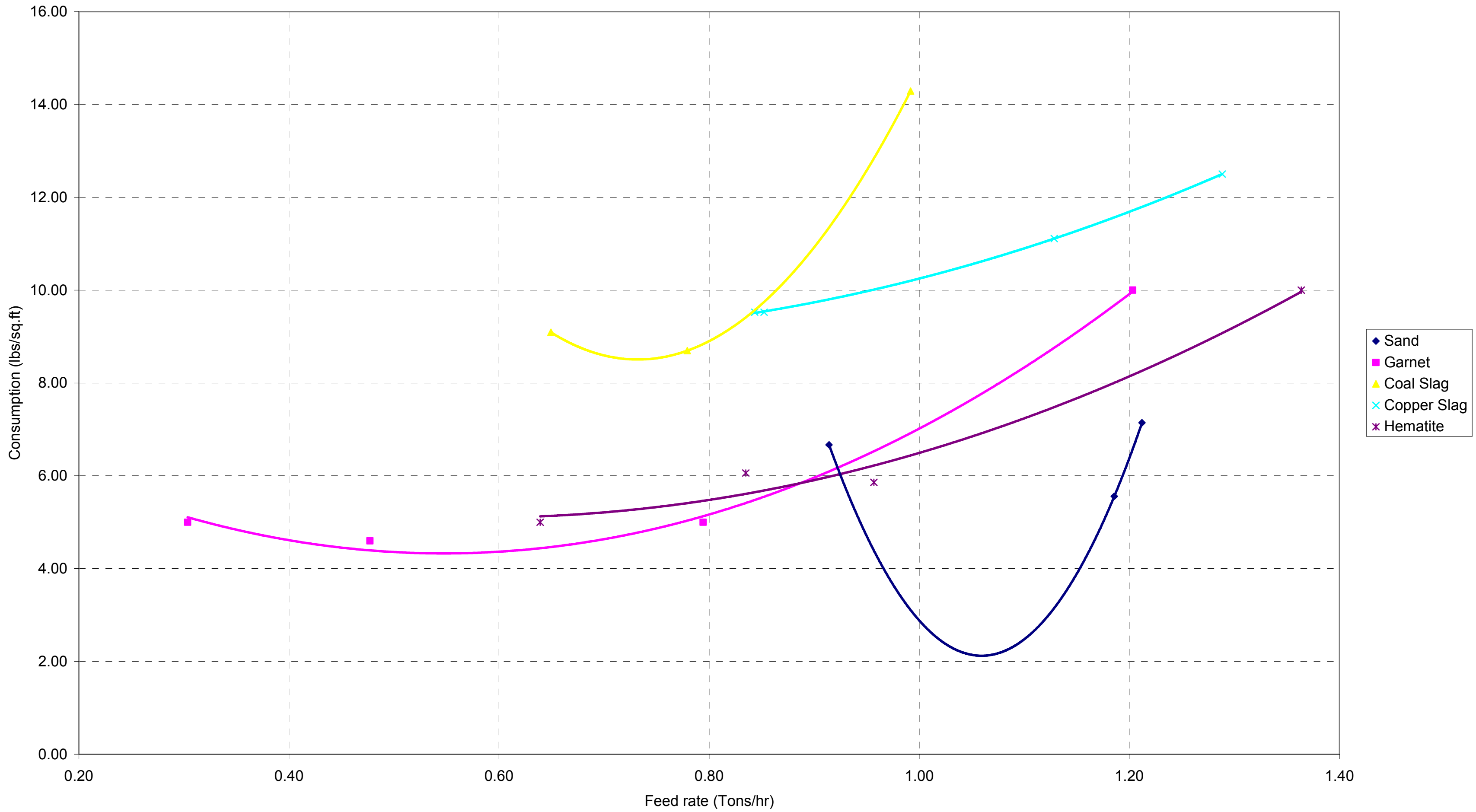
6 Bazooka Nozzle

Graph 16. Productivity Rate Trends at 80psi



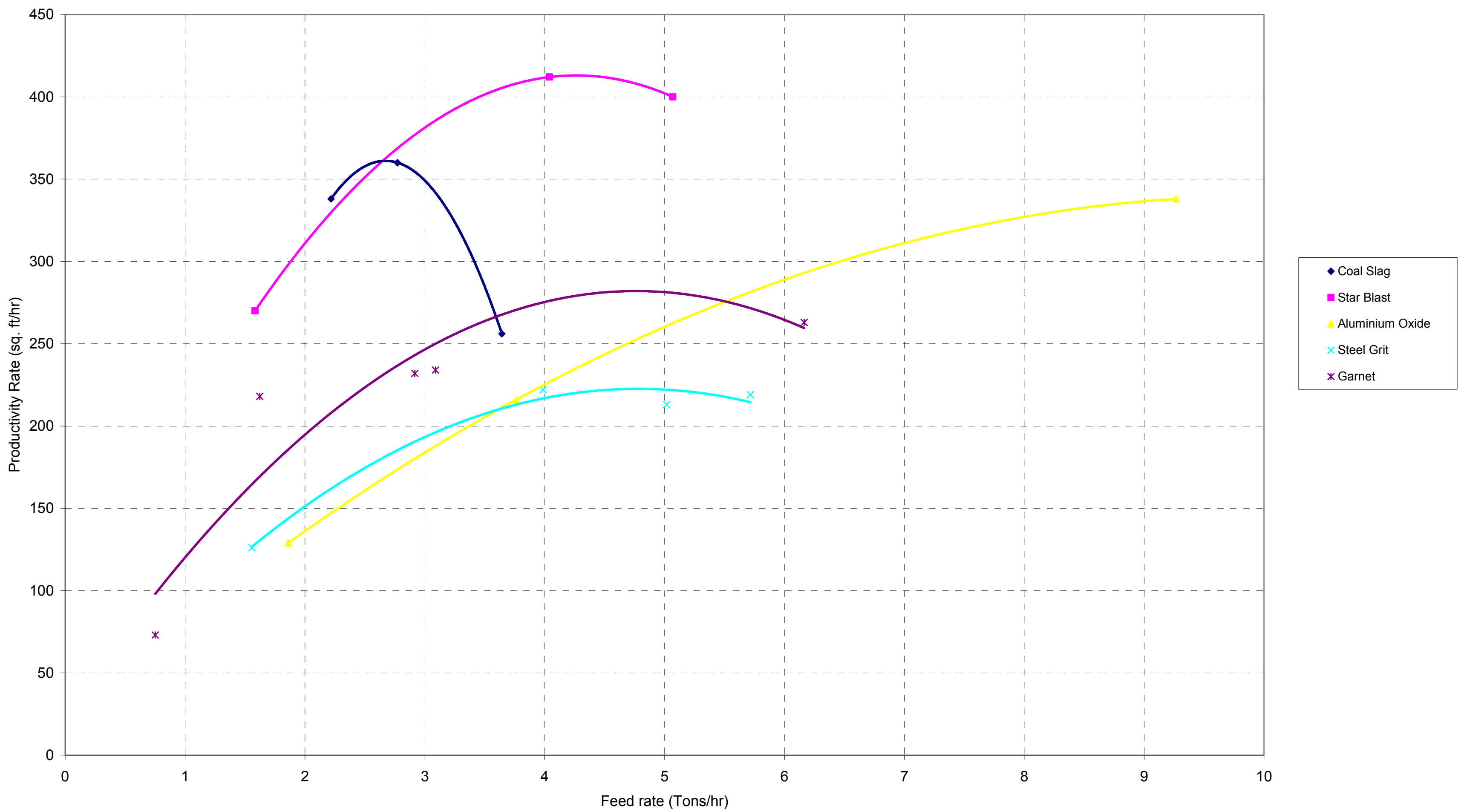
6 Double Venturi Nozzle

Graph 17. Consumption Rate Trends at 80psi



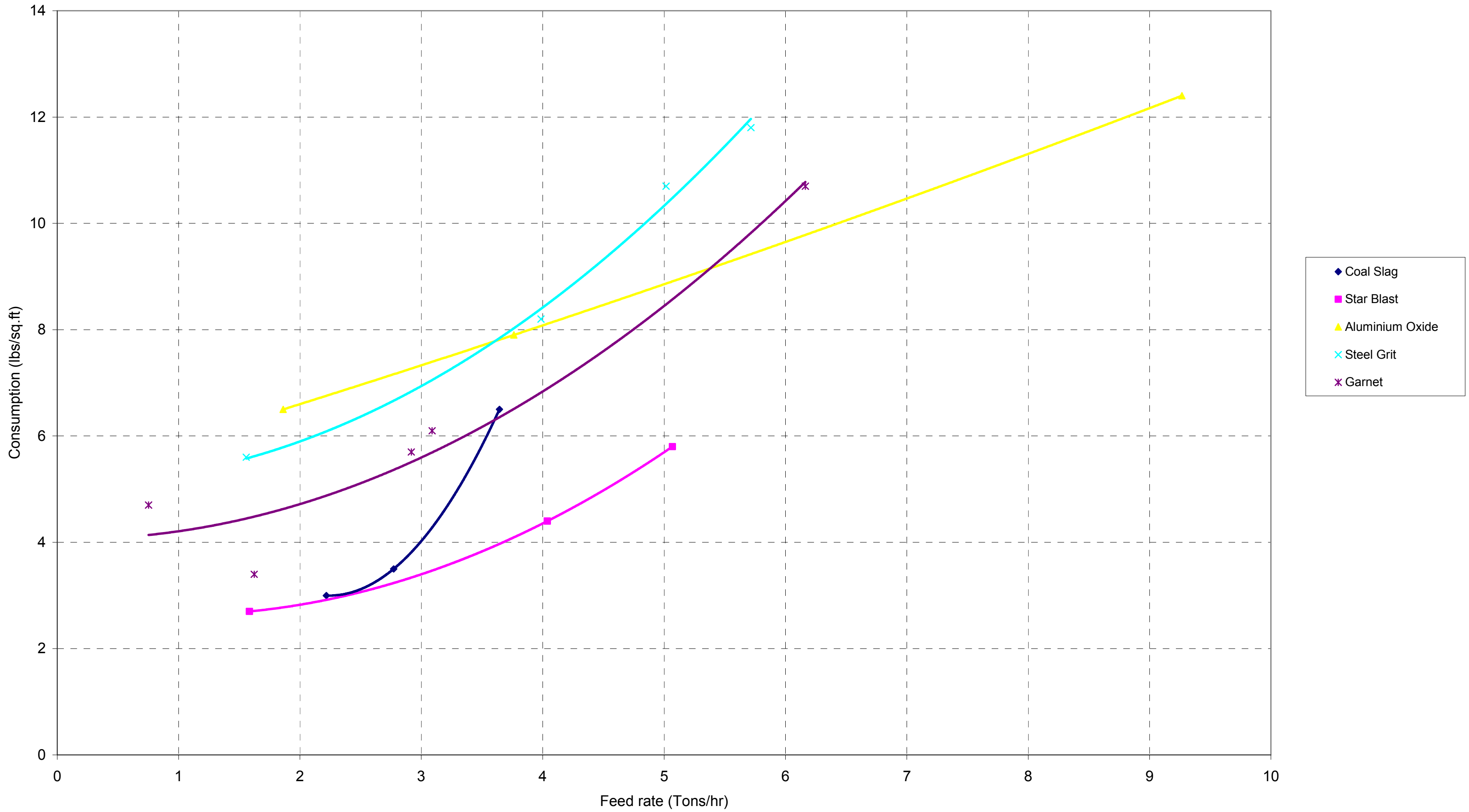
6 Double Venturi Nozzle

Graph 18. Productivity Rate Trends at 100 psi



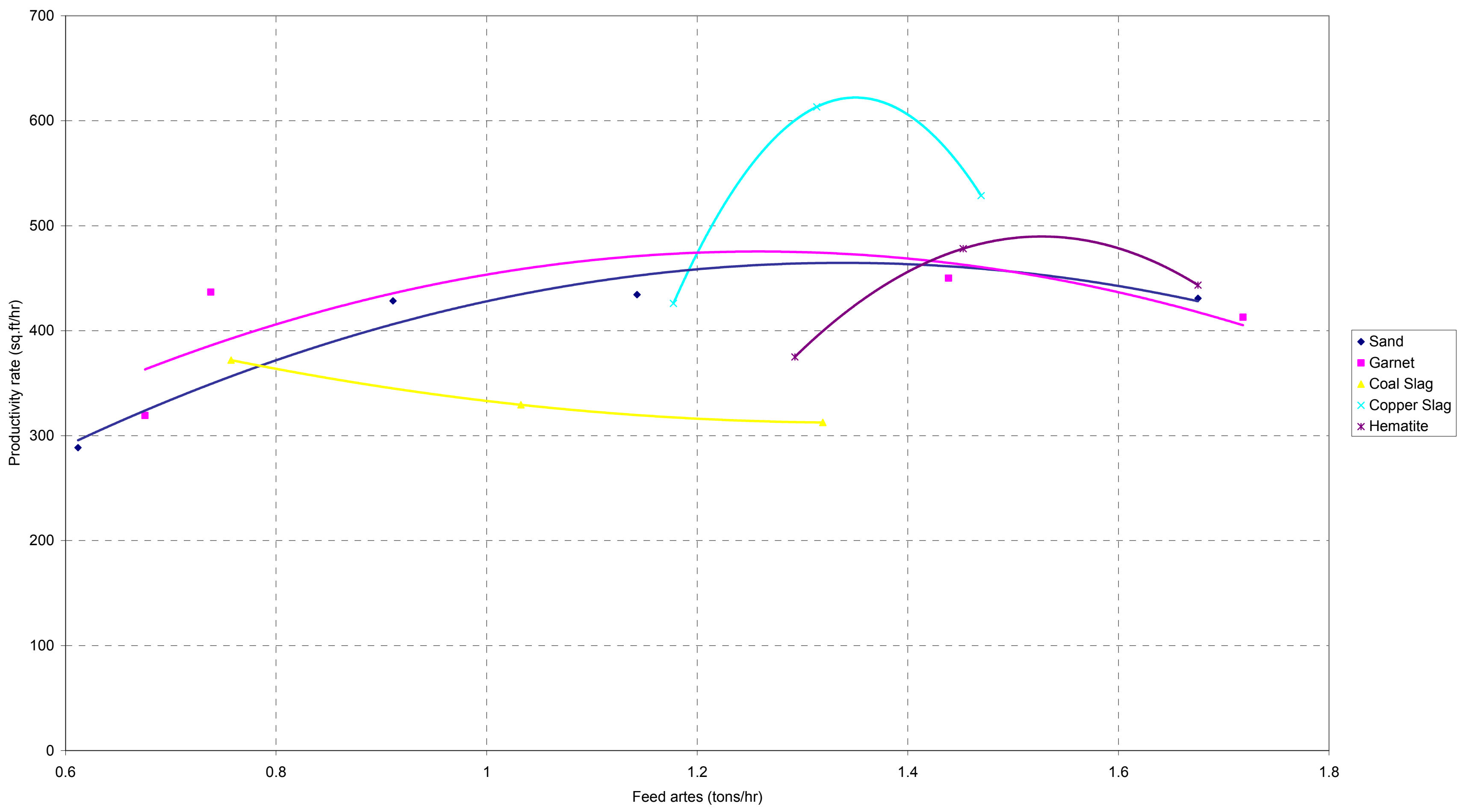
8 Bazooka Nozzle

Graph 19. Consumption Rate Trends at 100 psi



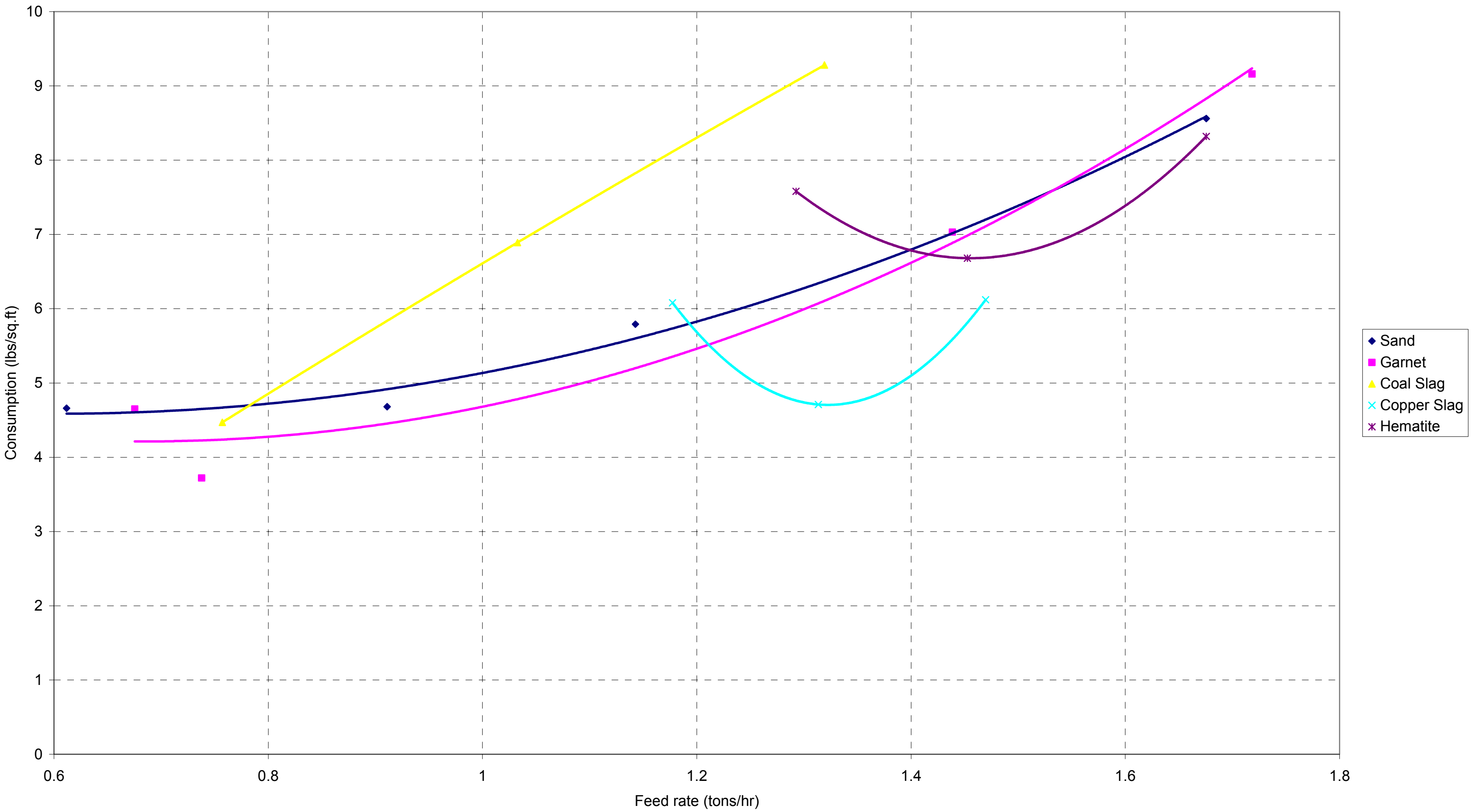
8 Bazooka Nozzle

Graph 20. Productivity Rate Trends at 122psi



6 Bazooka Nozzle

Graph 21. Consumption Rate Trends at 122psi



6 Bazooka Nozzle

Table 5.1. Equations of relationships for different abrasives

Abrasive	80 psi					100psi					122psi				
	X-Values	Productivity	R^2	Consumption	R^2	X-Values	Productivity	R^2	Consumption	R^2	X-Values	Productivity	R^2	Consumption	R^2
Sand	(0.91, 1.21)	$y = -14365x^2 + 30785x - 15836$	1	$y = 215x^2 - 456x + 243$	1		--------		--------		(0.61, 1.67)	$y = -320x^2 + 857- 109$	0.94	$y = 3.48x^2 - 4.19x + 5.85$	0.99
Garnet	(0.3, 1.2)	$y = -690.06x^2 + 1194.9x\ 172.15$	0.98	$y = 13.11x^2 - 14.35x + 8.25$	0.99	(0.75, 6.16)	$y = -11.43x^2 + 108.92x + 22.64$	0.84	$y = 0.18x^2 - 0.03x + 4.06$	0.94	(0.67, 1.71)	$y = -331.2x^2 + 833.15x - 48.53$	0.54	$y = 4.70x^2 - 6.44x + 6.41$	0.97
Coal Slag	(0.64, 0.99)	$y = -1510x^2 + 2465x - 806$	1	$y = 85.7x^2 - 125x + 54.4$	1	(2.21, 3.64)	$y = 1.78x^2 - 7.99x + 11.96$	1	$y = -111.57x^2 + 596.39x\ 435.86$	1	(0.75, 1.31)	$y = 171x^2 - 460x + 622$	1	$y = -0.79x^2 + 10.21x - 2.80$	1
Copper Slag	(0.84, 1.28)	$y = -176x^2 + 448x - 56.8$	0.99	$y = 6.91x^2 - 8.01x + 11.34$	0.99		--------		--------		(1.17, 1.46)	$y = -6559.3x^2 + 17713x - 11337$	1	$y = 65.331x^2 - 172.79x + 118.96$	1
Hematite	(0.63, 1.36)	$y = -1112x^2 + 2441x - 959$	1	$y = 22.3x^2 - 41.7x + 25.3$	1		--------		--------		(1.29, 1.67)	$y = -2092x^2 + 6388x - 4387$	1	$y = 33.9x^2 - 98.6x + 78.5$	1
Star Blast		--------		--------		(1.5, 5.06)	$y = -19.94x^2 + 169.97x + 50.80$	1	$y = 0.19x^2 - 0.38x + 2.82$	1		--------		--------	
Aluminium Oxide		--------		--------		(1.86, 9.26)	$y = -3.18x^2 + 63.6x + 21.5$	1	$y = 0.01x^2 + 0.67x + 5.2$	1		--------		--------	
Steel Grit		--------		--------		(1.55, 5.71)	$y = -9.23x^2 + 88.32x + 11.48$	0.97	$y = 0.21x^2 - 0.04x + 5.12$	0.99		--------		--------	

Note: X- Feed rates in Tons/ hr
Y- Productivity in sq.ft/hr
Y- Consumption in lbs/sq.ft

Table 5.2. Summary of abrasive productivity and consumption for different feed rates

80 psi, # 6 Double Venturi Nozzle

Feed Rate Ranges (Tons/hr)	Highest		Productivity Rates ←		Lowest
0.6 - 0.8	Garnet	Hematite	Coal Slag	Copper Slag	Sand
0.8 - 1.0	Garnet	Hematite	Sand	Copper Slag	Coal Slag
1.0 - 1.2	Sand	Hematite	Garnet	Copper Slag	Coal Slag
	Lowest		→ Consumption Rates		Highest

100 psi, # 8 Bazooka Nozzle

Feed Rate Ranges (Tons/hr)	Highest		Productivity Rates ←		Lowest
2.0 - 3.0	Star Blast	Coal Slag	Garnet	Steel Grit	Aluminium Oxide
3.0 - 4.0	Star Blast	Coal Slag	Garnet	Steel Grit	Aluminium Oxide
4.0 - 5.0	Star Blast	Garnet	Aluminium Oxide	Steel Grit	Coal Slag
	Lowest		→ Consumption Rates		Highest

122 psi, # 6 Bazooka Nozzle

Feed Rate Ranges (Tons/hr)	Highest		Productivity Rates ←		Lowest
1.0 - 1.2	Garnet	Sand	Coal Slag	Copper Slag	Hematite
1.2 - 1.4	Copper Slag	Garnet	Sand	Hematite	Coal Slag
1.4 - 1.6	Hematite	Copper Slag	Sand	Garnet	Coal Slag
	Lowest		→ Consumption Rates		Highest

6.0 CONCLUSIONS

The following are the conclusions of this study:

- The equations developed in this study enable us to determine optimum pressures and feed rate conditions to obtain increased productivity and low consumption rates.
- The comparative performance tables developed enable us to select the most productive and least waste generating abrasive for 80, 100, and 122 psi pressures within mentioned feed rate ranges.
- Operations within the ranges of feed rates for respective abrasives provided in the Table 5.2 would result in increased productivity.
- Looking at the graphs for the productivity and consumption rate trends, it can be concluded that at 80 psi pressure, Garnet is the most productive and least waste generating abrasive for feed rates less than 1 ton/hr. Coal slag is least productive with highest waste generation for feed rates greater than 0.8 tons/hr.
- At 80 psi, abrasives like hematite and garnet do not disintegrate much, reuse can be considered, thereby reducing the cost of operation. But, reusing is expected to increase particulate emissions. Depending upon the various criteria, various abrasive materials can be selected by the user. The cost of abrasive material is a major factor to be considered in the economic calculations.
- At 100 psi, it can be concluded that Aluminium Oxide is the most productive and least waste generating abrasive for feed rates less than 4 ton/hr. Star Blast is least productive with highest waste generation for any feed rate.

- At 122 psi, it can be concluded that Garnet is the most productive and least waste generating abrasive for feed rates less than 1.4 ton/hr. Hematite is least productive with highest waste generation.

7.0 RECOMMENDATIONS

The following are the recommendations of the study:

- Further experiments need to be conducted to develop relationships for all the subject abrasives at the three pressures.
- Additionally, there is a need for experiments to be conducted to develop relationships between feed rate and productivity, and consumption rates to achieve different surface finishes.
- This study is based on data derived from experiments conducted at University of New Orleans as well as literature review. Hence it has the limitations of using varying test procedures. Such differences would affect the consistency of the applications utilizing the equations derived from this data. Thereby studies have to be conducted with consistent test procedures to generate data.
- Parallel studies are being conducted by GCRMTC to study performance of various abrasives at common conditions. These results are expected to yield better predictive models which should be referred before use of these equations.
- A study conducted with uniform feed rates ranges, standard nozzles, and at 80, 100, and 122 psi pressures would enable development of a superior mathematical models that would include both pressure and feed rate as variables to obtain productivity and consumption rates.

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APPENDICES

APPENDIX - A

TEST PLAN

TEST PLAN

Objective

To develop optimum feed rates, productivity rates, and consumption rates for different abrasives in shipyard blasting operations.

Test Procedure

Controlled environmental tests were conducted to ensure accurate mass balance between spent abrasives and collected wastes. Tests were conducted using five abrasives viz. Sand, Coal Slag, Copper Slag, Hematite, and Garnet. A 10ft x 8ft steel plate of 5/16th inch thickness with primer coating was used as test plate. A surface profile of Near White Finish was used as target conditions. The blast pot was loaded with known quantities of abrasive material and was used for blasting under two nozzle pressures namely 80psi and 122psi. The time taken for operation was noted using a stop watch. The area cleaned was measure using a measuring tape. Micro-valve fitted to the blasting machine was used to vary feed rates by increasing or decreasing the number of turns on it. After blasting operation, final weight of the blasting machine was noted and hence, optimum feed rates, productivity rates, and consumption rates were developed.

Test Setup

Blasting machine (blast pot), air preparatory equipment, generators, compressors, test plate, support for the plate, filter bag, blast gun, blast nozzle, pressure gauge and, exhaust system were used in the process. Apart from these equipment, there were various blast

media, drums in which the bulk spent media was collected, weighing scale and, fork lift that helped in the changing of the plates after each blasting operation.

Test Enclosure

The test enclosure was a simple PVC frame structure covered with a layer of 6-mil polyethylene sheet. The structure included a plywood floor. The approximate dimensions of the enclosure were 20 feet X 15 feet X 10 feet high. The Enclosure was designed in conformance with U.S Environmental Protection Agency (EPA) Method 204 to ensure ensured 100 percent capture efficiency.

Spent Abrasive Collection System

A negative pressure was created using an exhaust system to which an 8 inch-diameter flexible duct was connected from behind the test plate. The other end of was connected to a filter bag. The filter bag collected the spent media entrained in the exhaust air stream. The interior of the filter bag had an acrylic coating, which facilitated retrieval of the collected particles. The exhaust was switched on when the blasting operation started and switched off only after the collection process completed.

Air compressors

Two Air compressors were rented for the purpose, one for 80 psi pressure and the other for 122 PSI. The 80 psi compressor was diesel driven. The other compressor was electricity driven, which was driven with the help of a generator due to the lack of specified power supply on site.

Fork lift

A forklift was used to change the plates after each operation.

Blasting machine (Blast Pot)

A Schmidt manufactured 6.5 cu ft 185 liter portable blasting machine was used in the testing. This portable blast pot was provided with 1-1/4 inch piping, pneumatic remote controls, combovalve, microvalve, 55 feet twin line control hose, deadman control and moisture separator. On the whole the equipment weighed about 385 lbs.

Air preparatory equipment

Moisture in the compressed air system contaminates both controls and the abrasive, causing damage to the bridge and not flow properly. To overcome this problem a Schmidt manufactured air preparatory system was introduced between the compressor and the blasting machine. The compressed air entering the air preparatory system passes through prefilter removing severe contaminants, particles and moisture before going to the cooler. The air then enters the lower tank of the air preparatory system where it expands and slows down, allowing the moisture to fall out. Next, air travels up through a stainless steel particulate filter or deliquescent tablets into the clean air manifold. The air then becomes cooler, cleaner and drier, with very little pressure drop.

Test plate

The shipyard provided the plate used for testing. Dimensions of the plate were 10 feet by 8 feet and had a thickness of 5/16 inch. Although the plate had an area 80 ft^2 to blast, a

foot on each side was not blasted in order to protect the polyethylene walls of the enclosure from tearing down due to over spray from the blast gun. The plate was painted with a primer and the blasting was done to remove the primer and to obtain a near white finish. Near white finish is the degree of cleaning which when viewed without magnification, at least 95 percent of the surface is free of all visible residue after blast cleaning

Support for the test plate

Test plate was supported by a metal stand, which was placed inside using the forklift. Under the legs of the support, rubber sheet was spread inorder to protect the plastic sheeting from tearing and to make the collection process easy.

Exhaust system

An 8-inch flexible duct was placed in one corner behind the test plate, which was connected to an exhaust pump. The amount of exhaust air calculated was approximately 800 standard cubic feet per minute (scfm). The 800 standard cubic feet per minute includes the 375 standard cubic feet per minute of blasting air and 425 cubic feet per minute of air let in into the enclosure through the natural draft openings. A natural draft opening is any permanent opening in the enclosure that remains open during the operation of the facility and is not connected to a duct in which fan is installed. The exhaust was designed to provide a 10-air change per hour to maintain a safe working atmosphere. The coarse particles settle down in the drum on which the pump was placed. The finer particles escaped from the drum and reached the filter, which was

connected to the pump on the other end. The lower end of the filter was fitted onto a drum. Before detaching the filter to collect the material, the filter bag was tapped so that any finer particles stuck to the bag, would drop down into the drum. The material collected in these two drums was weighed together and a sample was analyzed for particle size analysis.

Drums

Drums of 55-gallon volume with a polyethylene liner were used to collect the used abrasive from the enclosure. The abrasive filled drum was then rolled to ensure proper mixing of the material and sampling was done according to the American Standards for Testing and Materials (ASTM) standard C702, Method C.

Weighing scale

The weighing scale used, could measure from ½ pound to a maximum of 1200 pounds with accuracy. This scale was used to weigh the blasting machine before and after blasting operation, drums (with and without used abrasive), filter bag, fine dust collected and, the blast material loaded into the blast pot.

Blast nozzles

Double venturi nozzle was used at 80 psi pressure and Bazooka was used at 122 psi pressure. These nozzles were manufactured by Boride and were made of Tungsten Carbide.

Pressure gauge

A needle pressure gauge was used to ensure that the desired pressure was available at the nozzle. With the help of a needle, which was pierced into the blast hose at the blasting end, the pressure at the blasting end of the hose was determined.

VITA

Naveen Chillara was born in Narsapur, a small town in West Godavari district of Andhra Pradesh State, India. He graduated with a Bachelors Degree in Civil Engineering from Jawaharlal Nehru Technological University, Hyderabad, India. Mr. Chillara now works for Shaw Coastal, Inc. His work includes design and analysis of hydraulic structures like Sector gates, Saltwater Control Structures, and flood walls. He is also involved in coordination and conducting bathymetric surveys using state of art GPS and echo sounding equipment. His responsibilities include using various computer models in conducting hydrologic studies, processing GPS survey data, and design and analysis of oil field steel structures.