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# Cavitation-Resistant Coatings for Hydropower Turbines

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Construction Engineering Research Laboratory

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**Abstract:** Operating hydropower turbines to obtain the ultimate power output often results in cavitation (the rapid formation and collapse of vapor pockets in a flowing liquid in regions of very low pressure) in the turbine area. The level of cavitation typically destroys organic coatings in a relatively short time. Traditional metallizing to repair cavitation damage has resulted in unsatisfactory performance. Other coating systems, such as those deposited by High Velocity Oxygen Flame (HVOF), have been laboratory tested and shown to hold promise but have not been evaluated in actual long-term field applications.

This study evaluated HVOF-applied coating systems that hold promise for long-term cavitation resistance and apply the most promising products to turbine areas for long-term field performance data. Work consisted of evaluating existing published and unpublished data on cavitation-resistant materials and selecting the most promising systems for field application. Those systems were then applied to areas of a turbine to evaluate their long-term performance.

After 1 year, it is clear that many of the coatings have failed. Two of the coatings, however, appear to be virtually unchanged from the time of application and may be found to provide long-term resistance to damage caused by cavitation.

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# Preface

This demonstration was conducted for the Directorate of Civil Works, Headquarters, US Army Corps of Engineers (CECW) under the Civil Works Hydropower R&D Program. The proponent and technical monitor was Kamau B. Sadiki (CECW-CO-H).

The performing laboratory was the Materials and Structures Branch (CF-M) of the Facilities Division (CF), Construction Engineering Research Laboratory (CERL). The Project Manager was Alfred D. Beitelman (CF-M). Ryan Sollars of the Corps of Engineers Portland District Hydroelectric Design Center coordinated the field work. At the time this report was prepared, the Chief of CF-M was Vicki L. VanBlaricum, the Chief of CF was L. Michael Golish, and the Technical Director for Installations (CV-ZT) was Martin J. Savoie. The Deputy Director of CERL was Dr. Kirankumar Topudurti and the Director was Dr. Ilker Adiguzel.

CERL is an element of the US Army Engineer Research and Development Center (ERDC). The Commander and Executive Director of ERDC was COL Kevin J. Wilson and the Director was Dr. Jeffery P. Holland.

# Unit Conversion Factors

| Multiply | By | To Obtain |
|---|---|---|
| feet | 0.3048 | meters |
| horsepower (550 foot-pounds force per second) | 745.6999 | watts |
| inches | 0.0254 | meters |
| microinches | 0.0254 | micrometers |
| mils | 0.0254 | millimeters |
| square inches | 6.4516 E-04 | square meters |

# 1 Introduction

## Background

Hydropower turbines are often operated in a manner to obtain the ultimate amount of power output. Unfortunately, this frequently results in cavitation (the rapid formation and collapse of vapor pockets in a flowing liquid in regions of very low pressure) in the turbine area. The level of cavitation typically destroys organic coatings in a relatively short time. Traditional metallizing also has resulted in unsatisfactory performance. Other coating systems, such as those deposited by High Velocity Oxygen Flame (HVOF), have been laboratory tested and shown to hold good promise but have not been evaluated in actual long-term field applications. Field data would add validity to the laboratory data and perhaps provide long-term cavitation resistance.

## Objectives

The objectives of this work were to evaluate HVOF-applied coating systems that hold promise for long-term cavitation resistance and apply the most promising products to turbine areas for long-term field performance data.

## Approach

Work consisted of evaluating existing published and unpublished data on cavitation-resistant materials and selecting the most promising systems for field application. Those systems were then applied to areas of a turbine to evaluate their long-term performance.

# 2 Previous Research

## Civil works research

There were no previous studies on this subject found in the Corps of Engineers civil works research program. Work had been done in other programs, most notably in the Construction Productivity Advancement Research Program, which was published in a technical report entitled “Cavitation- and Erosion-Resistant Thermal Spray Coatings” (Boy et al. 1997). The report states the current practice for cavitation repair to be 308 and 309 weld rods, but laboratory data showed HVOF coatings to offer superior cavitation resistance as well as corrosion protection in the area of dissimilar metal boundaries. Although HVOF was used to demonstrate the field application of several coating materials, no data on the performance of the field applications were published.

Current cavitation repair practice within the Corps of Engineers typically consists of standard welding procedures. Cavitation repair performed recently at Corps of Engineers’ power plants include dams at Green Peter, Foster Lakes, OR; Lower Granite, Clarkston, WA; Ice Harbor, Burbank, WA; Lookout Point, Dexter, OR; Hills Creek, Lake, OR; and Carters, Ellijay, GA. The Corps’ corporate practice has been almost exclusively to use 308 and 309 weld rod for cavitation repair. No other material has been commonly used. The only example of other materials used for cavitation repair was Hydroloy weld rod used at Carters Dam in 2003.

## Literature search

A literature search was conducted to identify some recent studies and documents on metallic cavitation resistant coatings:

1. A. Kumar, Exotic Alloys for Cavitation Resistance: Passing the Tests, *Hydro Review*, Vol. 17:5 (1998):16–21.
2. P. March and J. Hubble, *Evaluation of Relative Cavitation Erosion Rates For Base Materials, Weld Overlays, and Coatings*, Report No. WR28-1-900-282, Norris, TN: Tennessee Valley Authority Engineering Laboratory (September 1996).
3. T. Spicher, *Hydro Wheels: A Guide to Maintaining and Improving Hydro Units*, Kansas City, MO: HCI Publications (1995).

4. R. Richard, P. Willis, and A. Kumar, *Application of Thermal Spray and Ceramic Coatings and Reinforced Epoxy for Cavitation Damage Repair of Hydroelectric Turbines*, USACERL Technical Report TR FM-93/01, Champaign, IL: US Army Construction Engineering Research Laboratory (March 1993).
5. Ashok Kumar, J. Boy, Ray Zatorski, and L.D. Stephenson, Thermal Spray and Weld Repair Alloys for the Repair of Cavitation Damage in Turbines and Pumps: A Technical Note, *Journal of Thermal Spray Technology*, Vol. 14(2): 177–182 (June 2005).
6. C. L. Cheng, C.T. Webster, and J.Y. Wong, *Reduction of Cavitation Erosion Damage on Hydraulic Structures through the Use of Coatings,* Report CEA No. 511G530, Montreal, Quebec: Canadian Electrical Association (May 1987).
7. P. R. Rodrigue, *Cavitation Pitting Mitigation in Hydraulic Turbines*, Final Report EPRIAP-4719 Project 1745-10, Vol. 1&2, Palo Alto, CA: Electric Power Research Institute (August 1986).
8. J. S. Baker, *Cavitation Resistant Properties of Coating Systems Tested on a Venturi Cavitation Testing Machine*, Denver, CO: Bureau of Reclamation, Research Laboratory and Services Division (January 1994).
9. O. F. Karr, J. B. Brooks, P. A. March, and J. M. Epps, Raccoon Mountain Pumped Storage Plant, Unit 3 Weld Overlay Field Test Inspection Report, Tennessee Valley Authority Report No. TVA/PBO/R&D-90/4 (May 1990).
10. R. Schwetzke and H. Kreye, Cavitation Erosion of HVOF Coatings, Conference paper from Thermal Spray 1996: Practical Solutions for Engineering Problems, C. C. Berndt, Ed., *ASM International*, 153–158.

## Manufacturers' products

A search of manufacturers of anti-cavitation and surface hardening coatings was conducted. It was determined that a large number of vendors sell products that are potentially useful for metallic anti-cavitation coatings. Table 1 lists those vendors found. These vendors all manufacture thermal coatings for surface hardening for cavitation or wear. There are more vendors than it was possible to test in a field location. Further reduction of potential vendors would be possible by ranking their cavitation performance versus a cavitation standard such as ASTM G32, and choosing the highest ranking vendors for comparative in-field testing. Each of the vendors was contacted asking for information on their anti-cavitation products being testing according to ASTM G32. The results of the inquiries are included in the notes in Table 1.

Table 1. Manufacturers of anti-cavitation and surface hardening coatings.

| Vendor | Product(s) | Contact | Notes |
|---|---|---|---|
| Powder Alloy Inc. | Thermal coatings, HVOF powders, plasma spray powders, plasma transferred arc powders, and metallizing wire | Scott Ostholthoff | Does not currently have any products tested to ASTM G32; though they do have anti-cavitation coatings |
| Voith Siemens - | Anti-cavitation coatings | | Voith is a turbine manufacturer having experience with cavitation problems. |
| Plasma-Tec | Ceramic Chrome Oxide thermal coatings | Christopher Wysong | Does not have any specific products for anti-cavitation; they recommended Wall Colomonoy products. |
| Surface Modification Systems | Thermal coatings | Rajan Bamola | Interested in helping with any studies; they recommended testing Amacor M, Nanosteel. Have done recent R&D combining metallic spray systems with a nonmetallic (epoxy) overcoat. |
| Plasma Thermal Coatings | Alumina Titania coatings | | No response. |
| Alacote | Thermal coatings | | No response. |
| Stellite | Thermal spray materials | Ken Whittenburg | Recommended Ultimet by Haynes or Deloro Stellite. |
| Flame Spray Technologies | Thermal coatings | Jim Perks | Primarily manufacturer of flame spray equipment; others provide the weld rod and powder materials. Interested in our research and willing to provide support on tools. They noted new HVOF system, JP5000, would allow thicknesses up to 0.5 in.; these new technology systems were not available during last series of anti-cavitation coating tests in 1997. |
| Climax Engineered Materials | Thermal coatings, unique metal powders and products | | No response. |
| Thermion | Thermion thermal coatings | | No response. |
| Ameteck Specialty Metal Products | Thermal coatings, including equivalents to Hastelloy and Inconel | | No response. |
| Bay State Surface Technology | Thermal coatings | | No response. |
| Carpenter Powder Products | Thermal coatings | | No response. |
| Saint Gobain Coatings | Thermal coatings | | No response. |

| Vendor | Product(s) | Contact | Notes |
|---|---|---|---|
| Ellison Surface Technologies | Thermal coatings | | No response. |
| Exline, Inc. | Thermex thermal coatings | Larry Pankratz | Exline does not currently have any products tested to ASTM G32, but they are interested in anti-cavitation coatings and testing. |
| Sulzer Metco | Thermal coatings, including Champro, Amdry, Mectoloy, and Thermospray | | No response. |
| Haiams | Thermal coatings | Daren Gansert | They market HA-1800 and were interested in future testing of their product. |
| Haynes Wire | Thermal coatings, maker of Ultimet and Hastalloy weld rod | Paul Manning | Recommended Deloro Stellite and the Ultimet product line as another possible product to test. |
| Höganäs | Thermal coatings, maker of Höganäs thermal surfacing powders | Lars-Ake Nilsson | None of their material has been tested to ASTM G32. |
| Mettech | Thermal coatings, maker of proprietary Axial III Thermal Spray Systems | | No response. |
| Osram Sylvania | Thermal coatings, maker of Osram Sylvania spray powders | | No response. |
| Plasma-Tec | Thermal coatings, maker of ALPHA 1800 arc spray coatings | | No response. |
| PolyMet Corporation | Thermal coatings, maker of PMET thermal spray wires | Richard Cook | No specific product has been tested to ASTM G32; they are interested in cavitation coatings. |
| UCT Coatings | Thermal spray anti-cavitation coatings | Wynn Atterbury | They have coatings tested to ASTM G32; interested in future testing, but their current product does not allow for field application. |
| Wall Colmonoy Corporation | Colmonoy | | Wall Colmonoy was not part of the market survey; they were recommended by Plasma-tec. |
| Amperit | AMPERIT and AMPERWELD hard surface coatings | | Amperit was not part of the market survey |
| Alstrom | Neyroco anti-cavitation coatings (nonmetallic, for reference only) | | Alstrom is a large turbine manufacturer with extensive experience with cavitation coatings and design issues. |

During the process of investigating metallic cavitation repair and prevention coatings, it was noted that there are many nonmetallic anti-cavitation coatings. Comparative testing between the metallic and nonmetallic coatings could be valuable, as nonmetallics used in small pump applications are a well-developed market segment and could be as good as or better than metallic anti-cavitation coatings. See this article for a typical example of a nonmetallic coating. Further market research into nonmetallic anti-cavitation coatings is beyond the scope of this program.

## Cavitation repair companies

Two cavitation repair companies were contacted to determine the methods they commonly use for cavitation repair. Mike Triggs, from Hydro Power Services (HPS), said they traditionally have used 308 and 309; however, HPS recommended using 309 only. HPS has used other exotic welding materials (e.g., Cavtec) with little success. Mallory Davis, from Powerhouse Inc., uses 309 for cavitation repair and does not recommend the exotic welding materials. Neither vendor had used thermal spray or other unique repair methods.

## Cavitation in the shipping industry

The US Navy repair yards in Washington State and Hawaii, as well as Dr. Richard P. Szwerc of the US Navy Advanced Propulsor Development Office, were contacted to determine what methods the Navy uses for cavitation repair. The response from the Navy was that, in general, their propellers did not cavitate; cavitation was not a problem. The few cavitation problems that they did have were generally repaired by traditional welding. For new propellers, the Navy has partnered with Rolls Royce to work on a new thermal spray anti-cavitation coating. Click on this link for more information.

In 2003, the Naval Sea Systems Command and National Surface Treatment Center gave a presentation entitled, "Rudder Coating Failures on Navy Ships." This report details some of the research the Navy performed on metallic and nonmetallic coatings. The Navy was unsuccessful in finding a reliable, corrosion- and cavitation-resistant metallic coating.

# 3 Field Application of Coatings

The Green Peter Dam was selected to test cavitation resistant coatings. Green Peter is on the Middle Santiam River in Oregon and is operated by the Corps of Engineers Portland District. Construction on the project was initiated in 1961 and completed in 1967. It has two 133-in.-diameter Francis runners rated at 55,000 HP at 265 ft head.

No formal cavitation inspection documentation was found; however, initial cavitation damage was documented with handwritten annotations within a few years of unit start up. At some point, perhaps 10 years ago, the runners were repaired for leading edge cavitation, which was thought to be due to temporary operational constraints. No additional information is known. The leading edges of the runners were repaired and have not shown damage since. The cavitation damage on the discharge side has been reoccurring and has continued to occur in approximately the same areas.

Cavitation damage on the suction side has been repaired with stainless steel weld overlay many times. For many years, this was done on a bi-annual basis, but recently repair has been performed yearly. The stainless overlay has reduced cavitation damage on the suction side of the runner. No photographs are available of the early cavitation repairs. However, some cost data are available for earlier fiscal years (FYs):

March 1999 to September 2001: $215,172.98

FY02: $140,907.87

FY04 to FY06: No work performed

FY07: $221,537.32

FY08: $98,621

Over the 10-year period, the Government spent at least $676,239.17 on cavitation repairs. Additional money was spent in FY09 with work performed by Government personnel.

## Preparation of cavitation areas for coating

Work was conducted on Green Peter Unit 2 in November 2009. Nine turbine runner buckets were repaired and included in the testing. The following levels of cavitation (see Figures 1 through 4) were observed:

RUNNER DISCHARGE SIDE AT BAND: Cavitation was present on every bucket, on the fillet between the bucket and the band. The area and extent of the damage was approximately the same in all locations.

RUNNER DISCHARGE SIDE AT CROWN: There was no evidence of cavitation damage on the suction side of the trailing edge of the blades at their connection to the crown.

RUNNER INLET SIDE AT CROWN: There was no evidence of cavitation damage on the suction side of the trailing edge of the blades at their connection to the crown.

Figure 1. Typical cavitation damage areas on lower one-third of suction side of buckets after approximately 1 year of operation since last repair.

Figure 2. Typical cavitation damage areas on upper one-third of suction side of buckets after approximately 1 year of operation since last repair.

Figure 3. Typical cavitation damage area showing that cavitation-prone area covers much of area near fillet on suction side of buckets.

Figure 4. Typical cavitation repair areas on discharge side of buckets.

Prior to application of the coatings, the existing cavitation was repaired on each of the test buckets. The base metal of the runner is cast steel, QQ-5-681, class 3. The repair conducted by site personnel consisted of fill welding the area with 309 stainless and grinding the repair smooth. The coating applicator Flame Spray Incorporated (FSI) then abrasive blasted the surfaces with aluminum oxide grit. The surface roughness of the substrate before coating as well as that of the applied coating was recorded and documented by FSI (see Appendix A). The sketches in this appendix show the average roughness (Ra) in microinches (1000 µ in. is equivalent to 1 mil or 0.001 in.). The sketches include a line indicating the direction the instrument was oriented while making the reading. The sketches also show the location of a number of spots indicating cavities remaining in the surface after the grinding and abrasive blasting. Such cavities are inevitable. Some of the larger holes show an estimated diameter (Ø) and depth (↓) in inches; however, the majority of the holes that are shown simply as spots were too small to accurately estimate.

## Application of HVOF coatings

Due to the size of the runner, only the cavitation on the bottom of the suction side of the blades was coated with resistant coatings. The cavitation near the leading edge and runner band is in a space restricted area, and the HVOF gun cannot easily reach this area; also, HVOF requires approximately an 18-in. offset for application.

The applicator attempted to apply each coating to a final thickness of 20 mils. Since it is not possible to measure this thickness without damaging the coating, the applicator developed a procedure of coating a piece of flat steel and measuring the added thickness with a micrometer after a given number of passes with the gun. After determining the number of passes required to deposit a 20-mil coating at a consistent spray speed, the applicator coated the test area and assumed the desired 20-mil coating was accomplished. Table 2 lists the coatings tested. Appendix B documents the application equipment used, the coating products applied and the equipment settings used for the application of each product. Coating materials applied to test specimens were also subjected to tensile testing, which is also documented.

Table 2. Cavitation-resistant coatings tested at Green Peter Unit 2.

| Bucket # | Coating |
|---|---|
| 1 | Nanosteel SHS 9172 |
| 2 | Vecalloy |
| 3 | Ultimet |
| 4 | Stellite 6 |
| 5 | Praxair 1350 VM |
| 6 | Amperit 588: Cr3C2-NiCr 75/25 |
| 7 | Amperit 584: Cr3C2-NiCr 75/25 |
| 8 | Stellite 21 |
| 16 | 309 (base material for reference) |

## Timeline of application

Monday 11-16-09: By 9:30 AM the Contractor had already started to unload equipment from a flatbed truck. The air-gas truck arrived with seven oxygen tank assemblies. The equipment was lowered into the penstock gallery. The HVOF console and the powder feeder were set up near the draft tube door. In the afternoon, it was discovered that the air tanks were too tall to pass underneath the penstocks. As a result, longer air hose was procured and delivered overnight from San Diego.

Tuesday 11-17-09: Following a site safety meeting to go over the work and any potential hazards, work was initiated to abrasive blast the sample areas with aluminum oxide abrasive for HVOF application. The repair area was measured and mapped (see Appendix A) for weld inclusions and defects as well as the surface finish. The HVOF equipment started, but a water pressure alarm kept the system from operating properly. It was found that a check valve in the water lines was obstructing the water flow. The

HVOF machine was connected to another water source and was tested, but it was too late in the day so the equipment was left set up for the following morning.

Wednesday 11-18-09: The sample areas were lightly blasted to remove any oxide that might have formed overnight. Each bucket was marked with an area of about 12 in. × 4 in. At the time of initial application, the temperature was 56.9°F, humidity 63.3%, and dew point 48°F. Bucket #1 was coated with Nanosteel 9172. The total application time was approximately 25 minutes. As bucket #7 was coated with Amperit 584, the applicator noted what appeared to be a small crack in the test application area, apparently from the existing weld repair. A photograph was taken and the coating material was applied. Bucket #5 was coated with Praxair 1350 VM. Bucket #6 was coated with Amperit 588. Bucket #4 was coated with Stellite 6. There was a miscommunication with the applicator, which resulted in bucket #8 being coated with Stellite 21. This bucket had not been repaired and had very minor cavitation. Bucket #3 was coated with Ultimet. Bucket #2 was coated with Vecalloy. All applications were finished in approximately 5 hours.

For each test material, the material was sprayed on the test area as well as on test specimens that will be tested by FSI for thickness and strength. Photographs were taken of each area before and after the HVOF coating application. Photographs were also taken of all the equipment and the process was videotaped. The coating was finished late afternoon, and the work area was cleaned and some equipment dismantled.

Thursday 11-9-09: The equipment was loaded onto a flatbed truck and the area cleaned. FSI left the Green Peter site at approximately 1 PM.

During the week of 11-23: An additional bucket (#16) was weld repaired to be the reference 309 bucket since all of the repaired buckets were used for testing materials. Reference photographs were taken of the bucket before and after the repair.

### Comments on application

There was very little visible smoke and the noise is similar to air-arcing, although slightly less.

The process has similar ventilation requirements to welding, without the danger of arc flash or a need for ultraviolet light protection. Heat is not intense when outside of the flame tip and does not require special shielding. The gun causes no damage when the tip of the flame is several feet from a surface.

The sample areas were chosen on the bottom of the runner because the JP-5000 gun cannot reach the cavitation areas on the leading edge; the gun is too large and there is a minimum offset of approximately 18 in. The minimum offset would be a disadvantage for some smaller turbines where space is very restricted.

The feeder and control unit need to be within about 20 ft of the application area, so the equipment needed to be staged close to the mandoor. In some applications, the hallway leading to the mandoor might be too small for the equipment.

Access to the work area was a problem for the oxygen tanks. The rest of the equipment was smaller and fairly easy to move. For any future applications, the maximum clearance under penstocks and the height of the air tanks need to be considered.

## One-year observations

1. Nanosteel SHS 9172: Excellent condition with ~0.5 sq in. of missing coating and a slight depression in the substrate.
2. Vecalloy: ~4-5 sq in. of bare substrate. Sharp edges indicate the coating broke off sharply as opposed to a wearing action. This is typical of an adhesion failure.
3. Ultimet: ~5 sq in. of bare substrate. Sharp edges indicate the coating broke off sharply as opposed to a wearing action. This is typical of an adhesion failure.
4. Stellite 6: Perfect condition. Several minor holes in substrate (reference Appendix A sketch) have not enlarged.
5. Praxair 1350 VM: About 75% of test area is bare substrate. Sharp edges indicate the coating broke off sharply as opposed to a wearing action. This is typical of an adhesion failure.
6. Amperit 588 Cr3C2-NiCr 75/25: There are bare areas including ~2 sq in. near the top of the test area, ~0.5 sq in. near the center of the area, and ~2 sq in. near the bottom of the area. Some of the edges are sharp while others are tapered.

7. Amperit 584 Cr3C2-NiCr 75/25: There are bare areas including ~1.5 sq in. near the top of the test area and ~4 sq in. in the lower area of the test area. The tapered edges indicate the coating was worn through.
8. Stellite 21: There are bare areas including ~2.5 sq in. near the top of the test area and ~5.5 sq in. near the bottom of the area. Sharp edges indicate the coating broke off sharply as opposed to a wearing action. This is typical of an adhesion failure. There appear to be cracks, especially on what seem to be thicker areas.
9. Control 309 base material (for reference): An area of light roughness and a slight depression (~1 sq in.) has developed due to cavitation.

# 4 Conclusions

The level of surface preparation provided was considered standard by the contractor applying the coatings and is in the same general range as is required for several coating processes. The documentation provided by the contractor shows the typical surface profile to be 3.0–3.5 mils. In comparison, organic (paint) coatings as specified by the Unified Facilities Guide Specification (UFGS) 099702 require a surface profile of 1.5–2.5 mils and UFGS 099701 requires a profile of 3–4 mils for 85/15 zinc/aluminum metalized coatings thicker than 14 mils.

The HVOF application process was capable of applying all of the coatings selected for this evaluation equally well. There was very little visible smoke and the noise was similar to air-arcing, although slightly less. The process had similar ventilation requirements to welding, without the danger of arc flash, or need for ultraviolet light protection. Heat is not intense when outside of the flame tip. It does not require special shielding, nor does the gun cause damage when the tip of the flame is several feet from a surface.

The sample areas were chosen on the bottom of the runner because the JP-5000 gun cannot reach the cavitation areas on the leading edge; the gun is too large and there is a minimum offset of approximately 18 in. The minimum offset would be a disadvantage for some smaller turbines where space is very restricted.

The feeder and control unit needed to be within about 20 ft of the application area, so the equipment needed to be staged close to the mandoor. In some applications, the hallway leading to the mandoor might be too small for the equipment.

Access to the work area was a problem for the oxygen tanks. The rest of the equipment was smaller and fairly easy to move. For any future applications, the maximum clearance under penstocks and the height of the air tanks should be considered.

After 1 year, the uncoated control area had developed an area of roughness that included a slight depression due to cavitation. The cavitation area was easy to identify because of its dull appearance in contrast to the bright and shiny appearance of the remainder of the area. (All areas of applied test coatings were very dull, making it impossible to identify the beginnings of cavitation damage.) This control area was effective in documenting the level of cavitation damage that is experienced in this area of the buckets.

Of all the coatings applied, the Stellite 6 application appeared to be providing the best performance after 1 year; however, the Nanosteel was also very good. Many of the observed failures had sharp edges indicating coating adhesion failure rather than erosion as the chief mode of failure.

Small holes were documented in the test areas after the fill weld and grinding process. These small holes did not appear to increase the level of cavitation damage to the immediate area or be detrimental to the performance of any of the coatings applied.

After 1 year, it is clear that many of the coatings have failed. Allowing these coatings to remain in place will have no adverse impact on the operation of the turbine. Two of the coatings appear to be virtually unchanged from the time of application and may be found to provide long-term resistance to damage caused by cavitation. It is recommended that all the coatings remain in place until the next regularly scheduled maintenance. At that time the performance should again be documented and compared to the uncoated control area.

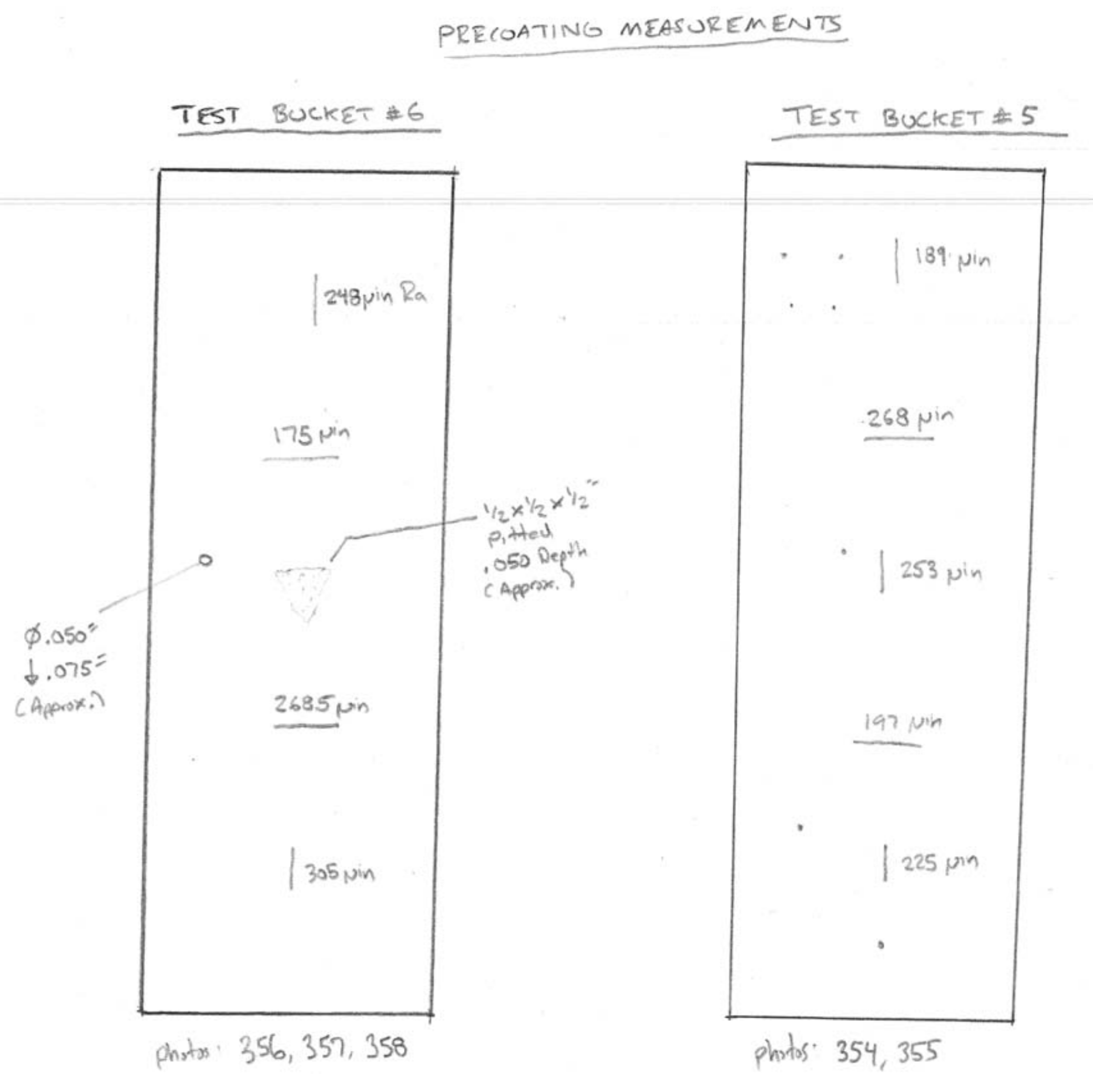
# References

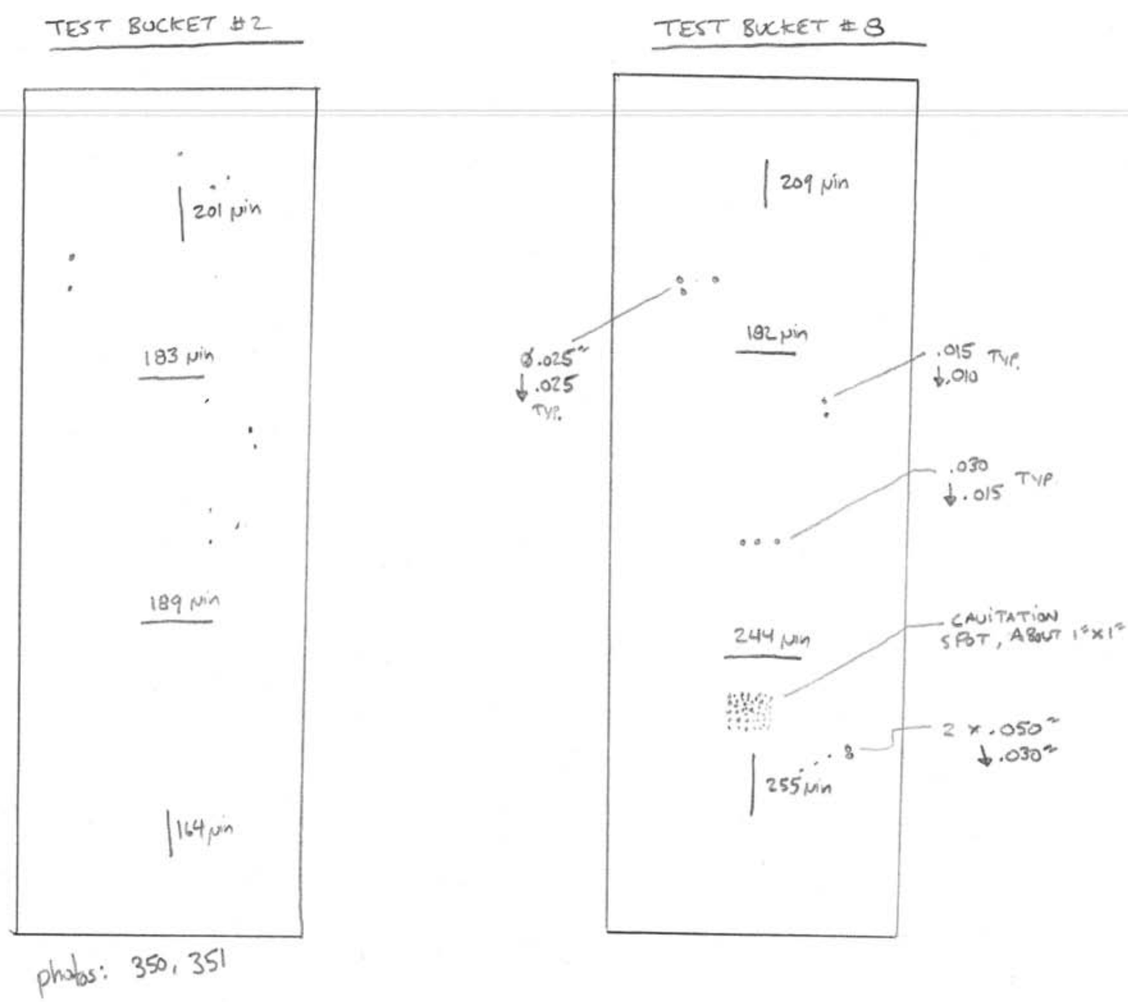
Boy, Jeffery H, Ashok Kumar, Patrick March, Paul Willis, and Herbert Herman. 1997. *Cavitation- and Erosion-Resistant Thermal Spray Coatings.* Technical report USACERL 97/118/ADA329272. Champaign, IL: US Army Construction Engineering Research Laboratory.

US Army Corps of Engineers (Civil Works). 2009. Unified Facilities Guide Specification (UFGS) 099701, Metallizing: Hydraulic Structures. Accessed at: http://www.wbdg.org/ccb/DOD/UFGS/UFGS%2009%2097%2001.00%2010.pdf

US Army Corps of Engineers (Civil Works). 2009. UFGS 099702. Painting: Hydraulic Structures. Accessed at: http://www.wbdg.org/ccb/DOD/UFGS/UFGS%2009%2097%2001.00%2010.pdf

# Appendix A: Hand Sketches of Test Areas

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183 µin
189 µin
164 µin
photos: 350, 351
TEST BUCKET #8
209 µin
182 µin
Ø.025"
↓.025
TYP.
.015 TYP.
↓.010
.030
↓.015 TYP.
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CAVITATION SPOT, ABOUT 1"x1"
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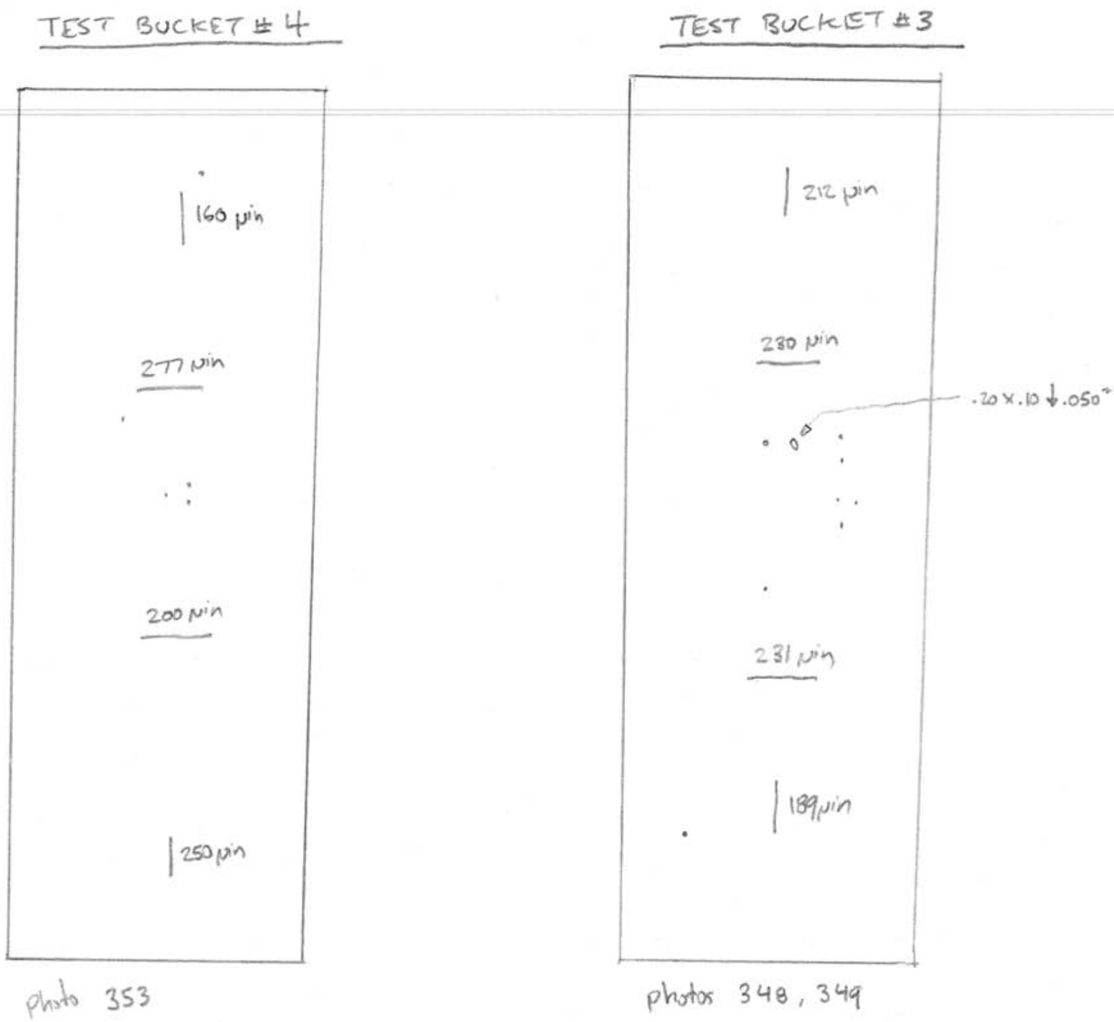
↓.030"
255 µin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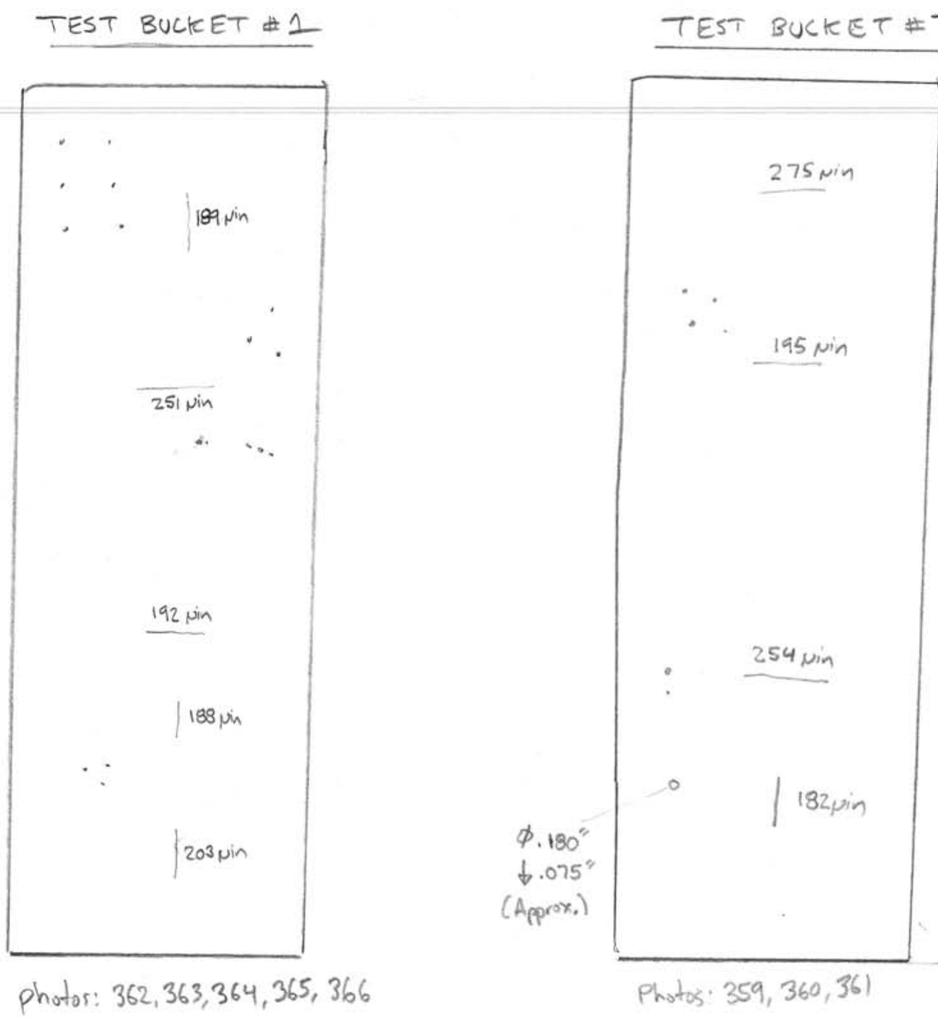
189 μin
photos 348, 349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251 μin
192 μin
188 μin
203 μin
photos: 362, 363, 364, 365, 366
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195 μin
254 μin
182 μin
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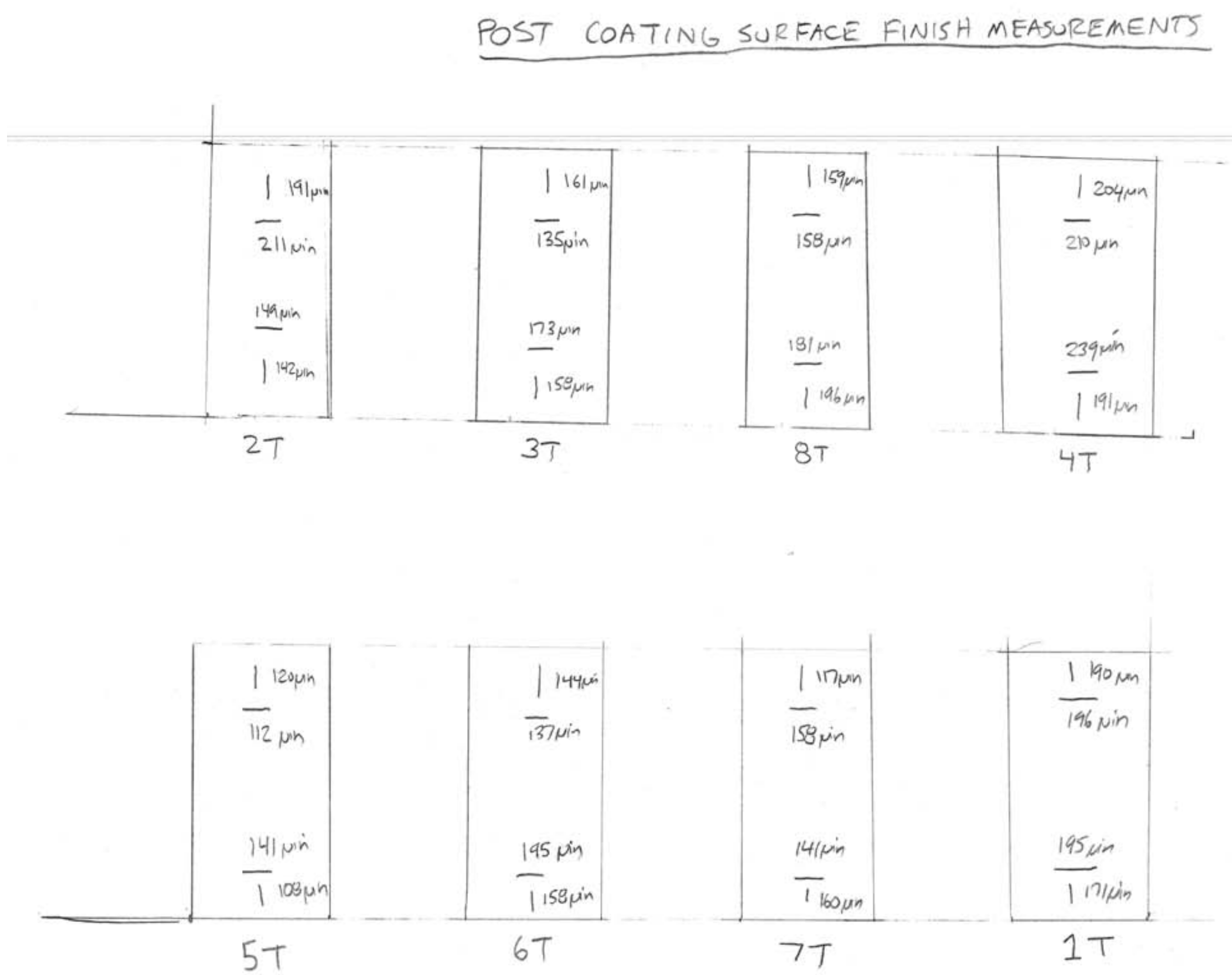
↓.075"
(Approx.)
Photos: 359, 360, 361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142µin
2T
161µin
135µin
173µin
158µin
3T
159µin
158µin
181µin
196µin
8T
204µin
210µin
239µin
191µin
4T
120µin
112µin
141µin
108µin
5T
144µin
137µin
195µin
158µin
6T
171µin
158µin
141µin
160µin
7T
190µin
196µin
195µin
171µin
1T

# Appendix B: Material Documentation and Application Equipment Settings

## Materials tested

FSI
FLAME SPRAY INC.

MATERIALS

| MATERIAL | DESIGNATION | LOT # | DESIGNATION |
|---|---|---|---|
| NanoSteel | SHS 9172 HV1 | 08-50 | 1T |
| Vecalloy | Vecalloy | 07-227 | 2T |
| Deloro Stellite | Ultimet | 5090137-2 | 3T |
| Praxair | CO-106-1 (Stellite 6) | 46 | 4T |
| Praxair | 1350VM | 418 | 5T |
| H.C.Starck | Amperit 588.074 | 4100900 | 6T |
| H.C.Starck | Amperit 584.1 | 4220840 | 7T |
| Deloro Stellite | Stellite 21 | 5090136-2 | 8T |

## Equipment used

FSI
FLAME SPRAY INC.

### EQUIPMENT
### HVOF JP 5000 SYSTEM

The TAFA JP-5000 uses an elegantly simple and effective design to produce High Pressure HVOF (HP/HVOF) coatings of incomparable quality. Coating benefits include:
- High and controllable coating density
- High and controllable coating hardness
- High bond strength (test adhesive fails before coating)
- Coating thickness exceeding 1/2" (12.7 mm)
- Smoother as-sprayed finish In addition to the outstanding coating quality, the JP-5000 delivers spray rates four times higher than typical HVOF systems.

JP 5000 CONSOLE


POWDER FEEDER
**MODEL 5500**


JP 5000 GUN

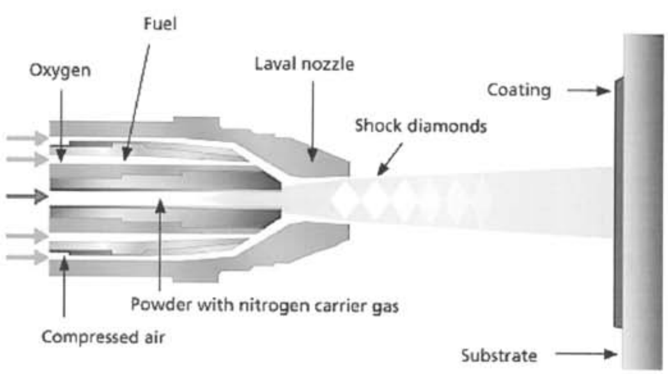
11

FLAME SPRAY INC.

**EQUIPMENT UTILIZED FOR COMPLIANCE WITH AMS 2447**
**JP 5000 HVOF THERMAL SPRAY SYSTEM DESCRIPTION.**

The primary component of this coating system is the JP 5000 gun. It is an internal combustion device. The combustion products are accelerated and exit the nozzle, producing a narrow jet of hot gas. Powder particles injected into the flame at the nozzle entrance are effectively heated and accelerated. When directed onto a target, they have sufficient thermal and kinetic energy to produce a dense, well-bonded coating.

The powder particles are introduced axially into the center of the exhaust jet. The powder particles melt or are softened from the heat and due to their high velocity, the particles when they hit a solid work piece are interlocked, resulting in a smooth coating that exhibits high bond strength, high density, and is usually very hard.




7

## Spray parameters

TAFA TECHNICAL DATA BULLETIN 1.9.2.2SH-1350VM

The Thermal Spray Technology Leader

# JP-5000 HP/HVOF

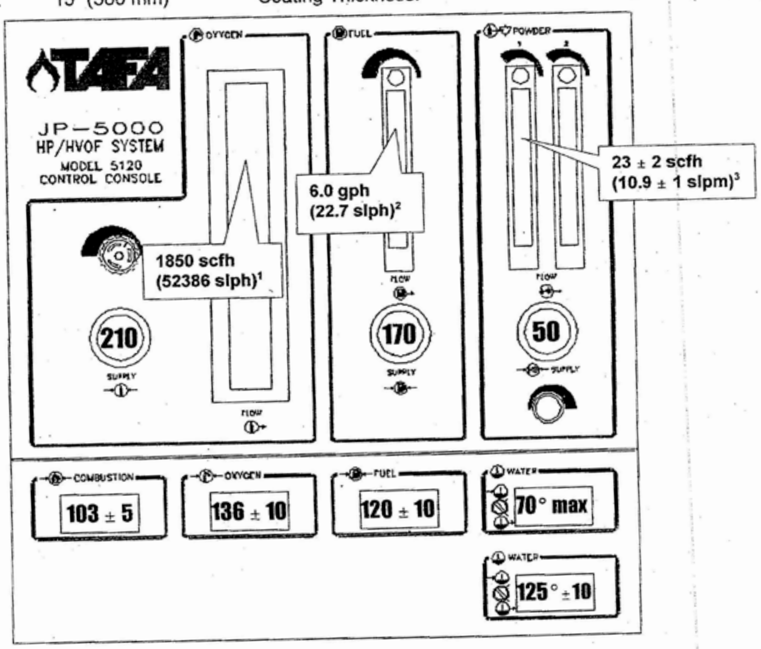
File: 1.9.2.2SH-1350VM
Issue: M11002
Supercedes: M10523

## Spray Parameters

### *TAFA 1350VM Tungsten Carbide – 10 Cobalt – 4 Chromium*

Although spray parameters vary, the following settings are recommended as good starting points for this coating. Some modifications may further enhance the coating quality.

| | | | |
|---|---|---|---|
| Spray System: | JP-5000 HP/HVOF | Spray Rate: | 13 lb/hr (98 g/min) |
| Gun Barrel: | 6" or 8" Length | Feeder Speed: | 330 rpm (6 Pitch Screw) |
| Spray Distance: | 15" (380 mm) | Coating Thickness: | 0.050" (1.3 mm) |




1. **Oxygen Flow** - The above flow setting is based on 210 psi supply pressure. For different supply pressures, use the Pressure Correction Chart in the Operation Section of the Manual to determine the correct flow for scfh specified above.
2. **Fuel Flow** - Users of older control consoles with a 0 to 100% tube in the fuel flowmeter should consult TAFA for the correct settings.
3. **Carrier Flow** - The needle valve above the powder feeder flowmeter should be left wide open and the flow should be adjusted with the needle valve on the console flowmeter. All flow rates are for nitrogen.

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1.9.2.2SH-1256F-1

TAFA

Worldwide Leaders in Thermal Spray Technologies
146 Pembroke Road Concord, NH 03301
TEL: 603/224-9585 FAX: 603/225-4342 HTTP://www.tafa.com

CD-106-1 STELLITE 6

# Technical Data

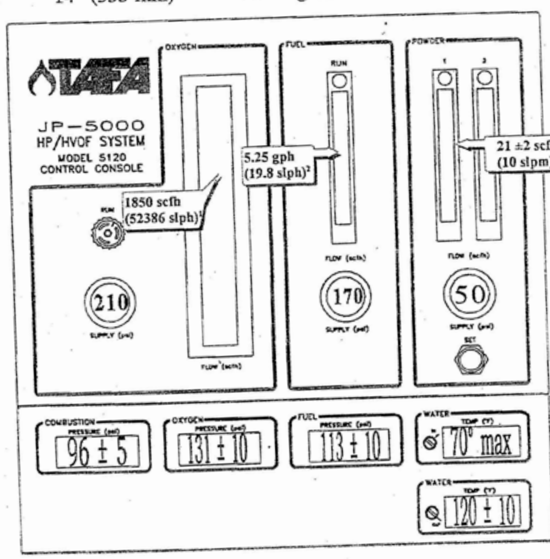
File: 1.9.2.2SH-1256F-1
Issue: M10409
Supersedes: J10831

## SPRAY PARAMETERS

1256F Cobalt-Chromium-Tungsten-Carbon (No. 6)

Although spray parameters vary, the following settings are recommended as good starting points for this coating. Some modification may further enhance the coating quality.

| | | | |
|---|---|---|---|
| Spray System: | JP-5000 HP/HVOF | Spray Rate: | 10 lb/hr (76 g/min) |
| Gun Barrel: | 8" Length | Feeder Speed: | 270 rpm (6 Pitch Screw) |
| Spray Distance: | 14" (355 mm) | Coating Thickness: | .100" [2.54 mm] |

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2. **Fuel Flow** - Users of older control consoles with a 0 to 100% tube in the fuel flowmeter should consult TAFA for the correct settings.
3. **Carrier Flow** - The needle valve above the powder feeder flowmeter should be left wide open and the flow should be adjusted with the needle valve on the console flowmeter. All flow rates are for nitrogen.

1.9.2.2SH-1269F

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ULTIMET

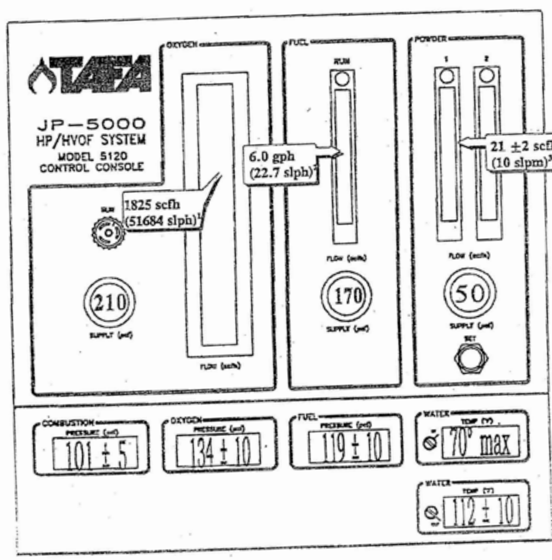
# Technical Data

File: 1.9.2.2SH-1269F
Issue: M10313
Original Issue

SPRAY PARAMETERS
1269F Alloy C-276

Although spray parameters vary, the following settings are recommended as good starting points for this coating. Some modifiction of the parameters may further enhance the coating quality.

| | | | |
|---|---|---|---|
| Spray System: | JP-5000 HP/HVOF | Spray Rate: | 10 lb/hr (76 g/min) |
| Gun Barrel: | 4" Length | Feeder Speed: | 410 rpm (6 Pitch Screw) |
| Spray Distance: | 15" (380 mm) | | |

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2. Fuel Flow - Users of older control consoles with a 0 to 100% tube in the fuel flowmeter should consult TAFA for the correct settings.
3. Carrier Flow - The needle valve above the powder feeder flowmeter should be left wide open and the flow should be adjusted with the needle valve on the console flowmeter. All flow rates are for nitrogen.

# SPRAY PARAMETERS JP 5000

Material VECALLOY

| | | | |
|---|---|---|---|
| Nozzle | 4" | Powder Feeder | 280 RPM |
| Spray Distance | 14" | Feed Rate | 10 lbs/hr |
| | | Cannister Pressure | 10 PSI |

| OXYGEN | COMBUSTION | WATER | POWDER |
|---|---|---|---|
| | | | |
| 1575 +/- 25 FLOW SCFH | 7 FLOW GPH | 7-8 FLOW GPH | 25 +/- 3 FLOW SCFH |
| | | | |
| 210 SUPPLY PSI | 170 SUPPLY PSI | | 50 SUPPLY PSI |
| | | | |
| 128 +/- 5 PRESSURE PSI | 100 +/- 2 PRESSURE PSI | 135 +/-20 PRESSURE PSI | 50 +/- 5 PRESSURE PSI |
| | | | |
| | | 100 +/- 20 TEMP OUT F | |
| | | | |
| | | 50 +/- 20 TEMP IN F | |

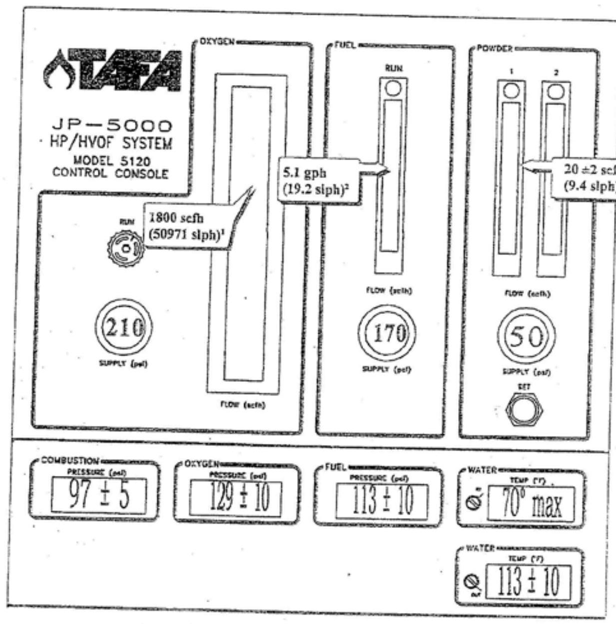
# TECHNICAL DATA BULLETIN

## JP-5000 HP/HVOF

### Spray Parameters — Nanosteel SHS 9172

Although spray parameters vary, the following settings are recommended as good starting points for this coating. Some modification may further enhance the coating quality.

| | | | |
|---|---|---|---|
| Spray System: | JP-5000 HP/HVOF | Spray Rate: | 10 lb/hr (76 g/min) |
| Gun Barrel: | 4" Length | Feeder Speed: | 270 rpm (6 Pitch Screw) |
| Spray Distance: | 14" (355 mm) | Coating Thickness: | 0.050" Maximum |




1. **Oxygen Flow** - The above flow setting is based on 210 psi supply pressure. For different supply pressures, use the Pressure Correction Chart in the Operation Section of the Manual to determine the correct flow for scfh specified above.
2. **Fuel Flow** - Users of older control consoles with a 0 to 100% tube in the fuel flowmeter should consult TAFA for the correct settings.
3. **Carrier Flow** - The needle valve above the powder feeder flowmeter should be left wide open and the flow should be adjusted with the needle valve on the console flowmeter. All flow rates are for nitrogen.

**TAFA** THE THERMAL SPRAY TECHNOLOGY LEADER **TECHNICAL DATA BULLETIN 1.9.2.2SH-1375VM**

# JP-5000 HP/HVOF

File: 1.9.2.2SH-1375VM
Issue: M10620
Supersedes: L10202

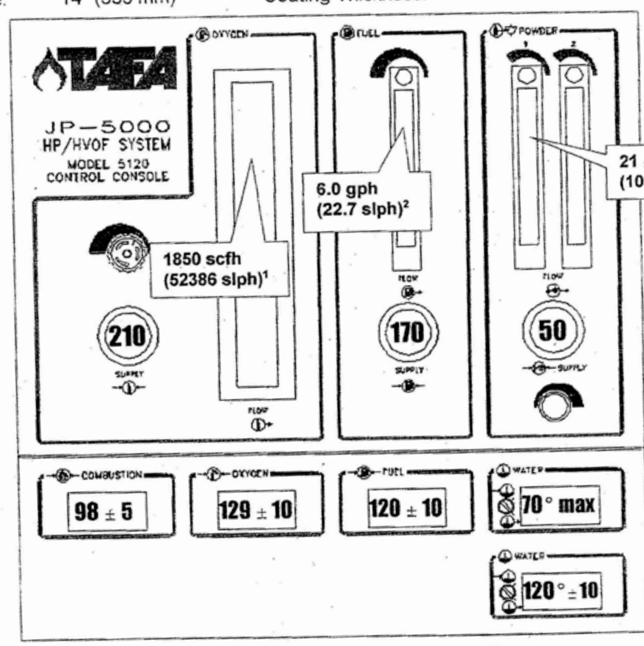
Amp ERIT 584

## Spray Parameters

### *TAFA 1375VM Chromium Carbide – 25 Nickel Chromium*

Although spray parameters vary, the following settings are recommended as good starting points for this coating. Some modifications may further enhance the coating quality.

| | | | |
|---|---|---|---|
| Spray System: | JP-5000 HP/HVOF | Spray Rate: | 7.7 lb/hr (58 g/min) |
| Gun Barrel: | 6" Length | Feeder Speed: | 475 rpm (6 Pitch Screw) |
| Spray Distance: | 14" (355 mm) | Coating Thickness: | 0.030" (0.76 mm) |

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2. **Fuel Flow** - Users of older control consoles with a 0 to 100% tube in the fuel flowmeter should consult TAFA for the correct settings.
3. **Carrier Flow** - The needle valve above the powder feeder flowmeter should be left wide open and the flow should be adjusted with the needle valve on the console flowmeter. All flow rates are for nitrogen.

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TAFA EUROPE, LTD
Burnt Meadow Road,
North Moons Moat, Redditch, WORCS, B98 9NZ, England

TAFA TECHNICAL DATA BULLETIN 1.9.2.2SH-1375VM

# JP-5000 HP/HVOF

File: 1.9.2.2SH-1375VM
Issue: M10620
Supersedes: L10202

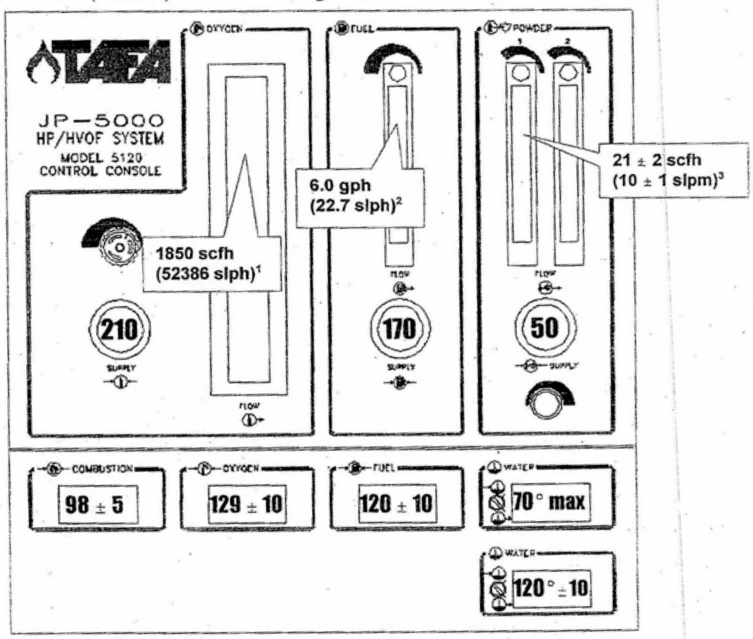
Amperit 588.

## Spray Parameters

*TAFA 1375VM Chromium Carbide – 25 Nickel Chromium*

Although spray parameters vary, the following settings are recommended as good starting points for this coating. Some modifications may further enhance the coating quality.

| | | | |
|---|---|---|---|
| Spray System: | JP-5000 HP/HVOF | Spray Rate: | 7.7 lb/hr (58 g/min) |
| Gun Barrel: | 6" Length | Feeder Speed: | 475 rpm (6 Pitch Screw) |
| Spray Distance: | 14" (355 mm) | Coating Thickness: | 0.030" (0.76 mm) |

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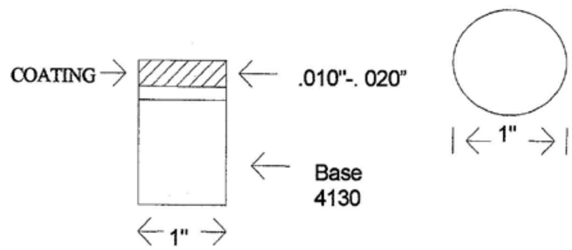
## Tensile testing

FLAME SPRAY INC.

**SKETCHES OF TEST SAMPLES**

**HVOF SYSTEM COATING**
**PER SPECIFICATION AMS 2447 and ASTM C- 633**

**TENSILE BARS:**




SAMPLE DIMENSIONS:

| SERIAL NUMBER | DIMENSION | | |
|---|---|---|---|
| | PRESPRAY | POST SPRAY | THICKNESS |
| 1T-1 | 2.202 | 2.222 | 0.020 |
| 1T-2 | 2.187 | 2.212 | 0.025 |
| 1T-3 | 2.190 | 2.203 | 0.013 |
| 2T-1 | 2.198 | 2.212 | 0.014 |
| 2T-2 | 2.185 | 2.203 | 0.018 |
| 2T-3 | 2.200 | 2.210 | 0.010 |
| 3T-1 | 2.190 | 2.205 | 0.015 |
| 3T-2 | 2.157 | 2.172 | 0.015 |
| 3T-3 | 2.188 | 2.204 | 0.016 |
| 4T-1 | 2.184 | 2.199 | 0.015 |
| 4T-2 | 2.194 | 2.210 | 0.016 |
| 4T-3 | 2.172 | 2.186 | 0.014 |
| 5T-1 | 2.160 | 2.174 | 0.014 |
| 5T-2 | 2.154 | 2.168 | 0.014 |
| 5T-3 | 2.166 | 2.180 | 0.014 |
| 6T-1 | 2.200 | 2.211 | 0.011 |
| 6T-2 | 2.183 | 2.194 | 0.011 |
| 6T-3 | 2.186 | 2.197 | 0.011 |
| 7T-1 | 2.187 | 2.199 | 0.012 |
| 7T-2 | 2.162 | 2.174 | 0.012 |
| 7T-3 | 2.195 | 2.206 | 0.011 |
| 8T-1 | 2.166 | 2.178 | 0.012 |
| 8T-2 | 2.168 | 2.180 | 0.012 |
| 8T-3 | 2.173 | 2.184 | 0.011 |

Average PSI :
1T 10399, 2T 8610, 3T 10346, 4T 9212, 5T 9818, 6T 10341, 7T 10123, and 8T 7976.
See report on following pages.

FSI FLAME SPRAY INC.

FORM 621

Nov 25, 2009

## AMS 2447 - Tensile Test Report

**Report No. 1467**

**Test Date** 25-Nov-09 Testing Machine STM-100KN

**Customer Name** US Army Green River Dam
**Operator** Ricky T.
**Material Top Coat** Nano Steel 9172 SHS
**WO Number** 18668 1T
**Lab Technician** Ricky Lee

**Purchase Order** W9127N-10-Q-
**Qty of Samples** 3
**Material Lot #** 08-050

**Load Cell S/N (TVI104866), Units (Lbs)** 22480
**Preload Value (Lbs)** 50
**Crosshead Speed (Inches / min) or Rate** 0.05
**Displacement Sensor** XHD_100 (XHD100)

| Test No | Specimen ID | Diameter (in) | Area (in ²) | Peak Force (lbs) | Peak Stress (psi) |
|---|---|---|---|---|---|
| 3174 | 18668-1T-02 | 0.991 | 0.771 | 8,045.8 | 10,431.1 |
| | | 100% Cohesive Adhesive Failure 0% Coating Failure | | | |
| 3175 | 18668-1T-03 | 0.990 | 0.770 | 8,281.4 | 10,758.3 |
| | | 100% Cohesive Adh. Failure 0% Coating Failure | | | |
| 3176 | 18668-1T-01 | 0.990 | 0.770 | 7,704.2 | 10,008.4 |
| | | 100% Coh. Adh. Failure 0% Coating Failure | | | |
| | Mean | 0.990 | 0.770 | 8,010.4 | 10,399.3 |
| | Median | 0.990 | 0.770 | 8,045.8 | 10,431.1 |

FSI FLAME SPRAY INC.
SOLVING PROBLEMS THAT SURFACE EVERYDAY

FORM"621

Nov 25, 2009

## AMS 2447 - Tensile Test Report

Report No. 1468

Test Date 25-Nov-09 Testing Machine STM-100KN

Customer Name US Army Green River Dam
Operator Ricky T.
Material Top Coat Vecalloy
WO Number 18668 2T
Lab Technician Ricky Lee

Purchase Order W9127N-10-Q-
Qty of Samples 3
Material Lot # 07-227

Load Cell S/N (TVI104866), Units (Lbs) 22480
Preload Value (Lbs) 50
Crosshead Speed (Inches / min) or Rate 0.05
Displacement Sensor XHD_100 (XHD100)

| Test No | Specimen ID | Diameter (in) | Area (in ²) | Peak Force (lbs) | Peak Stress (psi) |
|---|---|---|---|---|---|
| 3177 | 18668-2T-01 | 0.994 | 0.776 | 5,142.3 | 6,626.7 |
| | 100% Coh. Coating Failure 0% Adh. Failure | | | | |
| 3178 | 18668-2T-02 | 0.991 | 0.771 | 8,227.8 | 10,667.2 |
| | 100% Coh. Adh. Failure 0% Coating Failure | | | | |
| 3179 | 18668-2T-03 | 0.990 | 0.770 | 6,571.1 | 8,536.4 |
| | 30% Coh. Coating Failure 70% Coh. Adh. Failure | | | | |
| | Mean | 0.992 | 0.772 | 6,647.1 | 8,610.1 |
| | Median | 0.991 | 0.771 | 6,571.1 | 8,536.4 |
| | Std Dev | 0.002 | 0.003 | 1,544.2 | 2,021.3 |
| | Maximum | 0.994 | 0.776 | 8,227.8 | 10,667.2 |
| | Minimum | 0.990 | 0.770 | 5,142.3 | 6,626.7 |
| | Range | 0.004 | 0.006 | 3,085.5 | 4,040.5 |

By: [signature] Date: 11-25-09

Flame Spray, Inc. 4674 Alvarado Cyn Road San Diego, CA 92120 TEL (619) 283-2007 FAX (619) 283-5467

22

FSI FLAME SPRAY INC.

"SOLVING PROBLEMS THAT SURFACE EVERYDAY"

FORM 621

Nov 25, 2009

## AMS 2447 - Tensile Test Report

Report No. 1469

**Test Date** 25-Nov-09 Testing Machine STM-100KN

**Customer Name** US Army Green River Dam
**Operator** Ricky T.
**Material Top Coat** Stellite Ultimet
**WO Number** 18668-3T
**Lab Technician** Ricky Lee

**Purchase Order** W9127N-10-Q-
**Qty of Samples** 3
**Material Lot #** 5090137-2

**Load Cell S/N (TVI104866), Units (Lbs)** 22480
**Preload Value (Lbs)** 50

**Crosshead Speed (Inches / min) or Rate** 0.05
**Displacement Sensor** XHD_100 (XHD100)

| Test No | Specimen ID | Diameter (in) | Area (in ²) | Peak Force (lbs) | Peak Stress (psi) |
|---|---|---|---|---|---|
| 3180 | 18668-3T-01 | 0.993 | 0.774 | 8,365.2 | 10,801.6 |
| | | 100% Coh. Adh. Failure 0% Coating Failure | | | |
| 3181 | 18668-3T-02 | 0.990 | 0.770 | 7,857.0 | 10,206.9 |
| | | 100% Coh. Adh. Failure 0% Coating Failure | | | |
| 3182 | 18668-3T-03 | 0.978 | 0.751 | 7,535.2 | 10,030.6 |
| | | 100% Coh. Adh. Failure 0% Coating Failure | | | |
| | Mean | 0.987 | 0.765 | 7,919.1 | 10,346.4 |
| | Median | 0.990 | 0.770 | 7,857.0 | 10,206.9 |
| | Std Dev | 0.008 | 0.012 | 418.5 | 404.0 |
| | Maximum | 0.993 | 0.774 | 8,365.2 | 10,801.6 |
| | Minimum | 0.978 | 0.751 | 7,535.2 | 10,030.6 |
| | Range | 0.015 | 0.023 | 830.0 | 771.0 |

By: [signature] Date: 11-25-09

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FSI FLAME SPRAY INC.

SOLVING PROBLEMS THAT SURFACE EVERYDAY

FORM 621

Nov 25, 2009

## AMS 2447 - Tensile Test Report

Report No. 1470

Test Date 25-Nov-09 Testing Machine STM-100KN

Customer Name US Army Green River Dam
Operator Ricky T.
Material Top Coat Stellite 6
WO Number 18668
Lab Technician Ricky Lee

Purchase Order W9127N-10-Q-

Qty of Samples 3
Material Lot # 46

Load Cell S/N (TVI104866), Units (Lbs ) 22480
Preload Value ( Lbs ) 50

Crosshead Speed ( Inches / min ) or Rate 0.05
Displacement Sensor XHD_100 (XHD100)

| Test No | Specimen ID | Diameter (in) | Area (in ²) | Peak Force (lbs) | Peak Stress (psi) |
|---|---|---|---|---|---|
| 3183 | 18668-4T-02 | 0.991 | 0.771 | 7,841.7 | 10,166.6 |
| | | 100% Coh. Coating Failure 0% Adhesive Failure | | | |
| 3184 | 18668-4T-03 | 0.990 | 0.770 | 8,140.9 | 10,575.8 |
| | | 100% Coh. Coating Failure 0% Adh. Failure | | | |
| 3185 | 18668-4T-01 | 0.990 | 0.770 | 5,307.7 | 6,895.2 |
| | | 100% Coh. Coating Failure 0% Coh. Adh. Failure | | | |
| | Mean | 0.990 | 0.770 | 7,096.8 | 9,212.5 |
| | Median | 0.990 | 0.770 | 7,841.7 | 10,166.6 |
| | Std Dev | 0.001 | 0.001 | 1,556.6 | 2,017.3 |
| | Maximum | 0.991 | 0.771 | 8,140.9 | 10,575.8 |
| | Minimum | 0.990 | 0.770 | 5,307.7 | 6,895.2 |
| | Range | 0.001 | 0.002 | 2,833.2 | 3,680.6 |

By: [signature] Date: 11-25-09

Flame Spray, Inc. 4674 Alvarado Cyn Road San Diego, CA 92120 TEL (619) 283-2007 FAX (619) 283-5467

FSI FLAME SPRAY INC. SOLVING PROBLEMS THAT SURFACE EVERYDAY

FORM 621

Nov 25, 2009

## AMS 2447 - Tensile Test Report

Report No. 1471

Test Date 25-Nov-09 Testing Machine STM-100KN

Customer Name US Army Green River Dam
Operator Ricky T.
Material Top Coat Praxair 1350 VM
WO Number 18668-5T
Lab Technician Ricky Lee

Purchase Order W9127N-10-Q-
Qty of Samples 3
Material Lot # 418

Load Cell S/N (TVI104866), Units (Lbs) 22480
Preload Value (Lbs) 50

Crosshead Speed (Inches / min) or Rate 0.05
Displacement Sensor XHD_100 (XHD100)

| Test No | Specimen ID | Diameter (in) | Area (in ²) | Peak Force (lbs) | Peak Stress (psi) |
|---|---|---|---|---|---|
| 3186 | 18668-5T-02 | 0.992 | 0.773 | 7,535.7 | 9,750.1 |
| | 100% Coh. Adh. Failure 0% Coating Failure | | | | |
| 3187 | 18668-5T-03 | 0.991 | 0.771 | 7,637.9 | 9,902.3 |
| | 25% Coh. Coating Failure 75% Coh. Adh. Failure | | | | |
| 3188 | 18668-5T-01 | 0.993 | 0.774 | 7,590.8 | 9,801.7 |
| | 100% Coh. Adh. Failure 0% Coh. Coating Failure | | | | |
| | Mean | 0.992 | 0.773 | 7,588.1 | 9,818.0 |
| | Median | 0.992 | 0.773 | 7,590.8 | 9,801.7 |
| | Std Dev | 0.001 | 0.002 | 51.2 | 77.4 |
| | Maximum | 0.993 | 0.774 | 7,637.9 | 9,902.3 |
| | Minimum | 0.991 | 0.771 | 7,535.7 | 9,750.1 |
| | Range | 0.002 | 0.003 | 102.2 | 152.2 |

By: [signature] Date: 11-25-09

Flame Spray, Inc. 4674 Alvarado Cyn Road San Diego, CA 92120 TEL (619) 283-2007 FAX (619) 283-5467

FSI FLAME SPRAY INC.

SOLVING PROBLEMS THAT SURFACE EVERYDAY

FORM 621

Nov 25, 2009

## AMS 2447 - Tensile Test Report

Report No. 1472

**Test Date** 25-Nov-09 Testing Machine STM-100KN

**Customer Name** US Army Green River Dam
**Operator** Ricky T.
**Material Top Coat** Amperit 588.074
**WO Number** 18668-6T
**Lab Technician** Ricky Lee

**Purchase Order** W9127N-10-Q-
**Qty of Samples** 3
**Material Lot #** 4100900

**Load Cell S/N (TVI104866), Units (Lbs)** 22480
**Preload Value (Lbs)** 50

**Crosshead Speed (Inches / min) or Rate** 0.05
**Displacement Sensor** XHD_100 (XHD100)

| Test No | Specimen ID | Diameter (in) | Area (in ²) | Peak Force (lbs) | Peak Stress (psi) |
|---|---|---|---|---|---|
| 3189 | 18668-6T-02 | 0.976 | 0.748 | 7,507.9 | 10,035.3 |
| | 100% Coh. Adh. Failure 0% Coh. Coating Failure | | | | |
| 3190 | 18668-6T-03 | 0.993 | 0.774 | 7,852.3 | 10,139.3 |
| | 100% Coh. Adh. Failure | | | | |
| 3191 | 18668-6T-01 | 0.990 | 0.770 | 8,351.3 | 10,849.1 |
| | 100% Coh. Adh. Failure 0% Coating Failure | | | | |
| | Mean | 0.986 | 0.764 | 7,903.8 | 10,341.2 |
| | Median | 0.990 | 0.770 | 7,852.3 | 10,139.3 |
| | Std Dev | 0.009 | 0.014 | 424.0 | 442.9 |
| | Maximum | 0.993 | 0.774 | 8,351.3 | 10,849.1 |
| | Minimum | 0.976 | 0.748 | 7,507.9 | 10,035.3 |
| | Range | 0.017 | 0.026 | 843.4 | 813.8 |

By: [signature] Date: 11-25-09

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FSI FLAME SPRAY INC.

"SOLVING PROBLEMS THAT SURFACE EVERYDAY"

FORM 621

Nov 25, 2009

## AMS 2447 - Tensile Test Report

Report No. 1473

Test Date 25-Nov-09 Testing Machine STM-100KN

Customer Name US Army Green River Dam
Operator Ricky T.
Material Top Coat Amperit 584.1
WO Number 18668-7T
Lab Technician Ricky Lee

Purchase Order W9127N-10-Q-

Qty of Samples 3
Material Lot # 4220840

Load Cell S/N (TVI104866), Units (Lbs) 22480
Preload Value (Lbs) 50

Crosshead Speed (inches / min) or Rate 0.05
Displacement Sensor XHD_100 (XHD100)

| Test No | Specimen ID | Diameter (in) | Area (in ²) | Peak Force (lbs) | Peak Stress (psi) |
|---|---|---|---|---|---|
| 3192 | 18668-7T-02 | 0.973 | 0.744 | 7,458.2 | 10,030.4 |
| | 100% Coh. Adh. Failure 0% Coating Failure | | | | |
| 3193 | 18668-7T-03 | 0.990 | 0.770 | 7,945.9 | 10,322.4 |
| | 100% Coh. Adh. Failure 0% Coating Failure | | | | |
| 3194 | 18668-7T-01 | 0.959 | 0.722 | 7,235.9 | 10,017.7 |
| | 100% Coh. Adh. Failure 0% Coating Failure | | | | |
| | Mean | 0.974 | 0.745 | 7,546.7 | 10,123.5 |
| | Median | 0.973 | 0.744 | 7,458.2 | 10,030.5 |
| | Std Dev | 0.016 | 0.024 | 363.2 | 172.4 |
| | Maximum | 0.990 | 0.770 | 7,945.9 | 10,322.4 |
| | Minimum | 0.959 | 0.722 | 7,235.9 | 10,017.7 |
| | Range | 0.031 | 0.047 | 710.0 | 304.8 |

By: [signature] Date: 11-25-09

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FSI FLAME SPRAY INC. "SOLVING PROBLEMS THAT SURFACE EVERYDAY"

FORM 621

Nov 25, 2009

## AMS 2447 - Tensile Test Report

Report No. 1474

**Test Date** 25-Nov-09 Testing Machine STM-100KN

**Customer Name** US Army Green River Dam
**Operator** Ricky T.
**Material Top Coat** Stellite 21
**WO Number** 18668-8T
**Lab Technician** Ricky Lee

**Purchase Order** W9127N-10-Q-
**Qty of Samples** 3
**Material Lot #** 5090136-2

**Load Cell S/N (TVI104866), Units (Lbs)** 22480
**Preload Value (Lbs)** 50

**Crosshead Speed (Inches / min) or Rate** 0.05
**Displacement Sensor** XHD_100 (XHD100)

| Test No | Specimen ID | Diameter (in) | Area (in ²) | Peak Force (lbs) | Peak Stress (psi) |
|---|---|---|---|---|---|
| 3195 | 18668-8T-02 | 0.985 | 0.762 | 5,840.1 | 7,664.0 |
| | 100% Coh. Coating Failure 0% Adh. Failure | | | | |
| 3196 | 18668-8T-03 | 0.990 | 0.770 | 5,414.3 | 7,033.7 |
| | 100% Coh. Coating Failure 0% Adh. Failure | | | | |
| 3197 | 18668-8T-01 | 0.990 | 0.770 | 7,105.0 | 9,230.0 |
| | 100% Coh. Coating Failure 0% Adh. Failure | | | | |
| | Mean | 0.988 | 0.767 | 6,119.8 | 7,975.9 |
| | Median | 0.990 | 0.770 | 5,840.1 | 7,664.0 |
| | Std Dev | 0.003 | 0.004 | 879.3 | 1,130.9 |
| | Maximum | 0.990 | 0.770 | 7,105.0 | 9,230.0 |
| | Minimum | 0.985 | 0.762 | 5,414.3 | 7,033.7 |
| | Range | 0.005 | 0.008 | 1,690.6 | 2,196.3 |

By: [signature] Date: 11-25-09

Flame Spray, Inc. 4674 Alvarado Cyn Road San Diego, CA 92120 TEL (619) 283-2007 FAX (619) 283-5467

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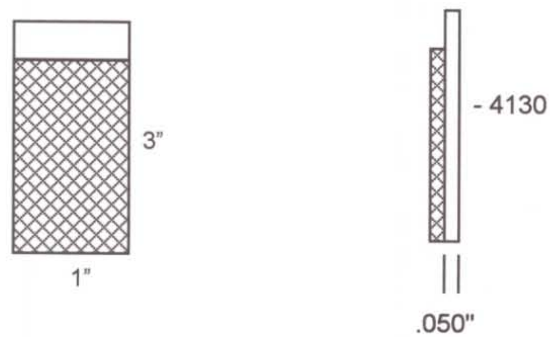
## Microstructure and hardness

FSI
FLAME SPRAY INC.

### HVOF SYSTEM COATING
### PER SPECIFICATION AMS 2447

**TEST PANELS:** (for Metallographic Examination including micro hardness)




SAMPLE DIMENSIONS:

| SERIAL NUMBER | DIMENSION | | |
|---|---|---|---|
| | PRESPRAY | POST SPRAY | THICKNESS |
| M1T | 0.051 | 0.070 | 0.019 |
| M2T | 0.051 | 0.071 | 0.020 |
| M3T | 0.050 | 0.072 | 0.022 |
| M4T | 0.051 | 0.070 | 0.019 |
| M5T | 0.051 | 0.068 | 0.017 |
| M6T | 0.051 | 0.058 | 0.010 |
| M7T | 0.051 | 0.059 | 0.011 |
| M8T | 0.051 | 0.069 | 0.018 |

Results were acceptable as shown in the Metallographic and Hardness report s in the following

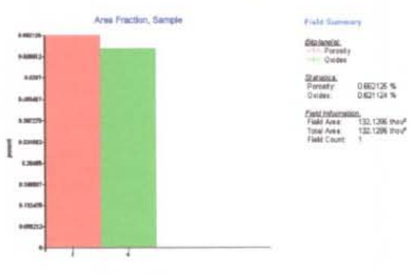
| | | |
|---|---|---|
| FSI FLAME SPRAY INC. | **Quality Control Microstructure Examination Report** | **Flame Spray Inc.**<br>**4674 Alvarado Canyon Rd.**<br>**San Diego, CA 92120**<br>**619-283-2007** |

| | | | |
|---|---|---|---|
| Work Order #: | 18668 | Application Spec: | AMS 2447 |
| Purchase Order #: | W9127N-10-Q-0002 | Lab. Technician: | Ricky Lee |
| Customer: | U.S. Army Green River Dam Project | Objective: | 200X |
| Material: | Nano Steel 9172 SHS Lot # 08-050 | Applicator: | Ricky T. |
| Date: | 11/23/09 | Sample Number: | 1T-B |

**Acceptance Criteria**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Cracks (None) | NONE | Porosity Max 2% | 0.66% | Interface Contaminatio n No Delam. | Acceptabl e No Delam. | Oxide Max 1%__ | 0.62% |

| | | | |
|---|---|---|---|
| Unmelted Particles Max 0.01% | Acceptable | Abrasive Particles | Acceptable |



FLAME SPRAY, INC.
4674 Alvarado Canyon Rd.
San Diego, CA. 92120

| | |
|---|---|
| **Test Performed** | Hardness Test-Vicker Profile |
| **Date:** | 11/24/2009 |
| **Lab W/O#** | 18668 |
| **Sample Number** | 18668-8T-A |
| **P.O#** | W9127N-10-Q-0002 |
| **Customer** | U.S. Army Green River Da |
| **Application Spec.** | AMS 2447 |
| **Acceptance Criteria** | 400 Min Avg. |
| **Total # of Measurements** | 10 |

| No | D1 | D2 | Avg D | HV |
|---|---|---|---|---|
| 1 | 34.21 | 35.02 | 34.62 | 464.30 |
| 2 | 35.82 | 36.72 | 36.27 | 422.89 |
| 3 | 35.09 | 37.21 | 36.15 | 425.70 |
| 4 | 32.92 | 34.72 | 33.82 | 486.38 |
| 5 | 34.69 | 35.76 | 35.23 | 448.36 |
| 6 | 32.33 | 32.86 | 32.60 | 523.63 |
| 7 | 31.76 | 32.53 | 32.15 | 538.39 |
| 8 | 35.82 | 36.4 | 36.11 | 426.65 |
| 9 | 33.6 | 34.66 | 34.13 | 477.59 |
| 10 | 34.97 | 34.96 | 34.97 | 455.05 |
| AVG | | | | 466.89 |

Laboratory Technician: ________

FLAME SPRAY, INC.
4674 Alvarado Canyon Rd.
San Diego, CA. 92120

| | |
|---|---|
| **Test Performed** | Hardness Test-Vicker Profile |
| **Date:** | 11/24/2009 |
| **Lab W/O#** | 18668 |
| **Sample Number** | 18668-1T-B |
| **P.O#** | W9127N-10-Q-0002 |
| **Customer** | U.S. Army Green River Da |
| **Application Spec.** | AMS 2447 |
| **Acceptance Criteria** | 375 Min Avg. |
| **Total # of Measurements** | 10 |

| No | D1 | D2 | Avg D | HV |
|---|---|---|---|---|
| 1 | 25.77 | 25.6 | 25.69 | 843.27 |
| 2 | 26.24 | 27.42 | 26.83 | 772.83 |
| 3 | 27.73 | 27.55 | 27.64 | 728.20 |
| 4 | 25.92 | 26.72 | 26.32 | 803.07 |
| 5 | 25.42 | 25.72 | 25.57 | 850.87 |
| 6 | 25.28 | 25.5 | 25.39 | 862.98 |
| 7 | 24.38 | 26.04 | 25.21 | 875.34 |
| 8 | 27.57 | 26.79 | 27.18 | 753.05 |
| 9 | 27.01 | 27.44 | 27.23 | 750.57 |
| 10 | 25.87 | 27.51 | 26.69 | 780.96 |
| AVG | | | | 802.11 |

Laboratory Technician:________________

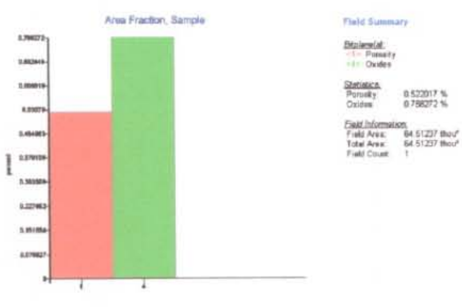
| | Quality Control Microstructure Examination Report | Flame Spray Inc.<br>4674 Alvarado Canyon Rd.<br>San Diego, CA 92120<br>619-283-2007 |
|---|---|---|
| FSI FLAME SPRAY INC. | | |

| | | | |
|---|---|---|---|
| Work Order #: | 18668 | Application Spec: | AMS 2447 |
| Purchase Order #: | W9127N-10-Q-0002 | Lab. Technician: | Ricky Lee |
| Customer: | U.S. Army Green River Dam Project | Objective: | 200X |
| Material: | Vecalloy Lot # 07-227 | Applicator: | Ricky T. |
| Date: | 11/23/09 | Sample Number: | 2T-B |

**Acceptance Criteria**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Cracks (None) | NONE | Porosity Max 2% | 0.52% | Interface Contamination No Delam. | Acceptable No Delam. | Oxide Max 1%__ | 0.75% |

| | | | |
|---|---|---|---|
| Unmelted Particles Max 0.01% | Acceptable | Abrasive Particles | Acceptable |



FLAME SPRAY, INC.
4674 Alvarado Canyon Rd.
San Diego, CA. 92120

| | |
|---|---|
| **Test Performed** | Hardness Test-Vicker Profile |
| **Date:** | 11/24/2009 |
| **Lab W/O#** | 18668 |
| **Sample Number** | 18668-2T-B |
| **P.O#** | W9127N-10-Q-0002 |
| **Customer** | U.S. Army Green River Da |
| **Application Spec.** | AMS 2447 |
| **Acceptance Criteria** | 500 Min. Avg. |
| **Total # of Measurements** | 10 |

| No | D1 | D2 | Avg D | HV |
|---|---|---|---|---|
| 1 | 29.79 | 31.12 | 30.46 | 599.80 |
| 2 | 27.01 | 28.37 | 27.69 | 725.57 |
| 3 | 25.28 | 26.95 | 26.12 | 815.73 |
| 4 | 25.78 | 27.02 | 26.40 | 798.21 |
| 5 | 26.84 | 27.3 | 27.07 | 759.19 |
| 6 | 29.74 | 29.78 | 29.76 | 628.14 |
| 7 | 24.8 | 26.41 | 25.61 | 848.55 |
| 8 | 25.38 | 26.14 | 25.76 | 838.36 |
| 9 | 25.58 | 27.03 | 26.31 | 803.99 |
| 10 | 28.16 | 28.02 | 28.09 | 705.05 |
| AVG | | | | 752.26 |

Laboratory Technician: ________

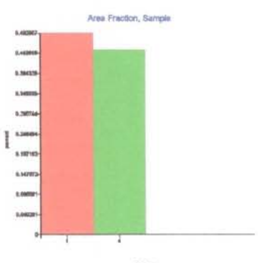
| | | |
|---|---|---|
| FSI FLAME SPRAY INC. | **Quality Control Microstructure Examination Report** | **Flame Spray Inc.**<br>**4674 Alvarado Canyon Rd.**<br>**San Diego, CA 92120**<br>**619-283-2007** |

| | | | |
|---|---|---|---|
| Work Order #: | 18668 | Application Spec: | AMS 2447 |
| Purchase Order #: | W9127N-10-Q-0002 | Lab. Technician: | Ricky Lee |
| Customer: | U.S. Army Green River Dam Project | Objective: | 200X |
| Material: | Stellite Ultimet Lot # 5090137-2 | Applicator: | Ricky T. |
| Date: | 11/23/09 | Sample Number: | 3T-B |

**Acceptance Criteria**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Cracks (None) | NONE | Porosity Max 2% | 0.49% | Interface Contamination No Delam. | Acceptable No Delam. | Oxide Max 1%__ | 0.45% |

| | | | |
|---|---|---|---|
| Unmelted Particles Max 0.01% | Acceptable | Abrasive Particles | Acceptable |




Field Summary

*Metalurgical:*
Porosity
Oxides

*Statistics:*
Porosity: 0.492907 %
Oxides: 0.451686 %

*Field Information:*
Field Area: 131.0947 thou²
Total Area: 131.0947 thou²
Field Count: 1

FLAME SPRAY, INC.
4674 Alvarado Canyon Rd.
San Diego, CA. 92120

| | |
|---|---|
| **Test Performed** | Hardness Test-Vicker Profile |
| **Date:** | 11/24/2009 |
| **Lab W/O#** | 18668 |
| **Sample Number** | 18668-3T-B |
| **P.O#** | W9127N-10-Q-0002 |
| **Customer** | U.S. Army Green River Da |
| **Application Spec.** | AMS 2447 |
| **Acceptance Criteria** | 400 Min Avg. |
| **Total # of Measurements** | 10 |

| No | D1 | D2 | Avg D | HV |
|---|---|---|---|---|
| 1 | 17.93 | 17.46 | 17.70 | 592.25 |
| 2 | 17.41 | 17.2 | 17.31 | 619.24 |
| 3 | 16.74 | 16.64 | 16.69 | 665.72 |
| 4 | 20.23 | 20.72 | 20.48 | 442.34 |
| 5 | 17.82 | 17.67 | 17.75 | 588.91 |
| 6 | 21.15 | 22.68 | 21.92 | 386.12 |
| 7 | 19.26 | 19.33 | 19.30 | 498.10 |
| 8 | 22.41 | 22.87 | 22.64 | 361.79 |
| 9 | 20.21 | 20.08 | 20.15 | 456.95 |
| 10 | 17.94 | 18.34 | 18.14 | 563.55 |
| AVG | | | | 517.50 |

Laboratory Technician:

| | | |
|---|---|---|
| FSI<br>FLAME SPRAY INC. | **Quality Control Microstructure Examination Report** | **Flame Spray Inc.<br>4674 Alvarado Canyon Rd.<br>San Diego, CA 92120<br>619-283-2007** |

| | | | |
|---|---|---|---|
| Work Order #: | 18668 | Application Spec: | AMS 2447 |
| Purchase Order #: | W9127N-10-Q-0002 | Lab. Technician: | Ricky Lee |
| Customer: | U.S. Army Green River Dam Project | Objective: | 200X |
| Material: | Praxair Co-106-1<br>Lot # 46<br>Ref. Stellite 6 | Applicator: | Ricky T. |
| Date: | 11/24/09 | Sample Number: | 4T-A |

**Acceptance Criteria**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Cracks (None) | NONE | Porosity Max 2% | 0.20% | Interface Contamination No Delam. | Acceptable No Delam. | Oxide Max 1%__ | 0.82% |
| Unmelted Particles | Acceptable | Abrasive Particles | Acceptable | | | | |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FLAME SPRAY, INC.
4674 Alvarado Canyon Rd.
San Diego, CA. 92120

**Test Performed** Hardness Test-Vicker Profile
**Date:** 11/24/2009
**Lab W/O#** 18668
**Sample Number** 18668-4T-A
**P.O#** W9127N-10-Q-0002
**Customer** U.S. Army Green River Da
**Application Spec.** AMS 2447
**Acceptance Criteria** 400 Min Avg.
**Total # of Measurements** 10

| No | D1 | D2 | Avg D | HV |
|---|---|---|---|---|
| 1 | 18.43 | 18.76 | 18.60 | 536.30 |
| 2 | 18.78 | 19.83 | 19.31 | 497.58 |
| 3 | 18.45 | 18.43 | 18.44 | 545.36 |
| 4 | 19.37 | 20.5 | 19.94 | 466.63 |
| 5 | 19.05 | 19.68 | 19.37 | 494.50 |
| 6 | 18.78 | 19.36 | 19.07 | 509.92 |
| 7 | 20.76 | 21.56 | 21.16 | 414.16 |
| 8 | 19.45 | 20.2 | 19.83 | 471.82 |
| 9 | 17.85 | 19.36 | 18.61 | 535.73 |
| 10 | 17.99 | 18.19 | 18.09 | 566.66 |
| AVG | | | | 503.87 |

Laboratory Technician: ____________

Page 1 of 1

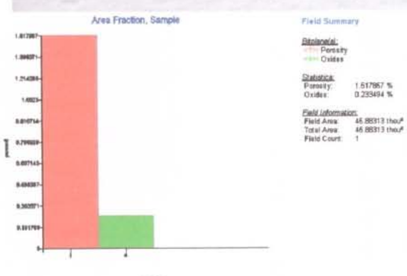
| | | |
|---|---|---|
| FSI FLAME SPRAY INC. | **Quality Control Microstructure Examination Report** | **Flame Spray Inc.<br>4674 Alvarado Canyon Rd.<br>San Diego, CA 92120<br>619-283-2007** |

| | | | |
|---|---|---|---|
| Work Order #: | 18668 | Application Spec: | AMS 2447 |
| Purchase Order #: | W9127N-10-Q-0002 | Lab. Technician: | Ricky Lee |
| Customer: | U.S. Army Green River Dam Project | Objective: | 200X |
| Material: | Praxair 1350VM Lot # 418 | Applicator: | Ricky T. |
| Date: | 11/23/09 | Sample Number: | 5T-A |

**Acceptance Criteria**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Cracks (None) | NONE | Porosity Max 2% | 1.51% | Interface Contamination No Delam. | Acceptable No Delam. | Oxide Max 1%__ | 0.23% |

| | | | |
|---|---|---|---|
| Unmelted Particles Max 0.01% | Acceptable | Abrasive Particles | Acceptable |



FLAME SPRAY, INC.
4674 Alvarado Canyon Rd.
San Diego, CA. 92120

| | |
|---|---|
| **Test Performed** | Hardness Test-Vicker Profile |
| **Date:** | 11/24/2009 |
| **Lab W/O#** | 18668 |
| **Sample Number** | 18668-5T-A |
| **P.O#** | W9127N-10-Q-0002 |
| **Customer** | U.S. Army Green River Da |
| **Application Spec.** | AMS 2447 |
| Acceptance Criteria | 1050 Min Avg. |
| **Total # of Measurements** | 10 |

| No | D1 | D2 | Avg D | HV |
|---|---|---|---|---|
| 1 | 23.53 | 23.2 | 23.37 | 1019.04 |
| 2 | 20.35 | 20.21 | 20.28 | 1352.66 |
| 3 | 20.58 | 21.32 | 20.95 | 1267.53 |
| 4 | 21.73 | 22.2 | 21.97 | 1153.09 |
| 5 | 25.48 | 26.41 | 25.95 | 826.45 |
| 6 | 22.16 | 23.09 | 22.63 | 1086.79 |
| 7 | 20.19 | 20.53 | 20.36 | 1342.05 |
| 8 | 21.6 | 22.33 | 21.97 | 1153.09 |
| 9 | 22.16 | 22.59 | 22.38 | 1111.22 |
| 10 | 24.05 | 24.76 | 24.41 | 934.04 |
| AVG | | | | 1124.60 |

Laboratory Technician: ____________

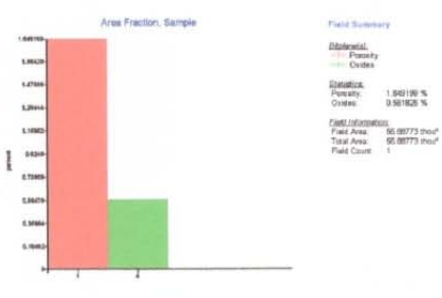
| | |
|---|---|
| **Quality Control Microstructure Examination Report** | **Flame Spray Inc.**<br>**4674 Alvarado Canyon Rd.**<br>**San Diego, CA 92120**<br>**619-283-2007** |

| Work Order #: | 18668 | Application Spec: | AMS 2447 |
|---|---|---|---|
| Purchase Order #: | W9127N-10-Q-0002 | Lab. Technician: | Ricky Lee |
| Customer: | U.S. Army Green River Dam Project | Objective: | 200X |
| Material: | Amperit 588.074 Lot # 4100900 | Applicator: | Ricky T. |
| Date: | 11/23/09 | Sample Number: | 6T-A |

**Acceptance Criteria**

| Cracks (None) | NONE | Porosity Max 2% | 1.84% | Interface Contamination No Delam. | Acceptable No Delam. | Oxide Max 1%__ | 0.56% |
|---|---|---|---|---|---|---|---|

| Unmelted Particles Max 0.01% | Acceptable | Abrasive Particles | Acceptable |
|---|---|---|---|



FLAME SPRAY, INC.
4674 Alvarado Canyon Rd.
San Diego, CA. 92120

| | |
|---|---|
| **Test Performed** | Hardness Test-Vicker Profile |
| **Date:** | 11/24/2009 |
| **Lab W/O#** | 18668 |
| **Sample Number** | 18668-6T-A |
| **P.O#** | W9127N-10-Q-0002 |
| **Customer** | U.S. Army Green River D |
| **Application Spec.** | AMS 2447 |
| **Acceptance Criteria** | 800 Avg. |
| **Total # of Measurements** | 10 |

| No | D1 | D2 | Avg D | HV |
|---|---|---|---|---|
| 1 | 15.38 | 15.37 | 15.38 | 784.46 |
| 2 | 15.34 | 14.52 | 14.93 | 831.92 |
| 3 | 14.96 | 15.18 | 15.07 | 816.54 |
| 4 | 14.83 | 14.68 | 14.76 | 851.78 |
| 5 | 13.64 | 13.96 | 13.80 | 973.75 |
| 6 | 13.74 | 14.85 | 14.30 | 907.48 |
| 7 | 13.64 | 12.74 | 13.19 | 1065.89 |
| 8 | 15.26 | 15.72 | 15.49 | 772.86 |
| 9 | 15.67 | 15.03 | 15.35 | 787.02 |
| 10 | 14.32 | 15.24 | 14.78 | 848.90 |
| AVG | | | | 864.06 |

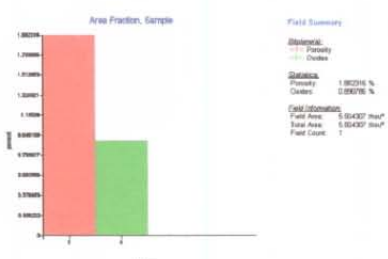
Laboratory Technician:________________

| | | |
|---|---|---|
| FSI FLAME SPRAY INC. | **Quality Control Microstructure Examination Report** | **Flame Spray Inc.<br>4674 Alvarado Canyon Rd.<br>San Diego, CA 92120<br>619-283-2007** |

| Work Order #: | 18668 | Application Spec: | AMS 2447 |
|---|---|---|---|
| Purchase Order #: | W9127N-10-Q-0002 | Lab. Technician: | Ricky Lee |
| Customer: | U.S. Army Green River Dam Project | Objective: | 200X |
| Material: | Amperit 584.1<br>Lot # 4220840 | Applicator: | Ricky T. |
| Date: | 11/23/09 | Sample Number: | 7T-B |

**Acceptance Criteria**

| Cracks (None) | NONE | Porosity Max 2% | 1.89% | Interface Contamination No Delam. | Acceptable No Delam. | Oxide Max 1%__ | 0.89% |
|---|---|---|---|---|---|---|---|
| Unmelted Particles Max 0.01% | Acceptable | Abrasive Particles | Acceptable | | | | |



FSI
FLAME SPRAY INC.

FLAME SPRAY, INC.
4674 Alvarado Canyon Rd.
San Diego, CA. 92120

| | |
|---|---|
| **Test Performed** | Hardness Test-Vicker Profile |
| **Date:** | 11/24/2009 |
| **Lab W/O#** | 18668 |
| **Sample Number** | 18668-7T-B |
| **P.O#** | W9127N-10-Q-0002 |
| **Customer** | U.S. Army Green River Da |
| **Application Spec.** | AMS 2447 |
| **Acceptance Criteria** | 800 Avg. |
| **Total # of Measurements** | 10 |

| No | D1 | D2 | Avg D | HV |
|---|---|---|---|---|
| 1 | 15.31 | 15.35 | 15.33 | 789.08 |
| 2 | 15.36 | 15.3 | 15.33 | 789.08 |
| 3 | 13.3 | 13.59 | 13.45 | 1025.85 |
| 4 | 14.8 | 15.35 | 15.08 | 816.00 |
| 5 | 13.58 | 12.84 | 13.21 | 1062.67 |
| 6 | 12.81 | 12.75 | 12.78 | 1135.38 |
| 7 | 12.89 | 13.68 | 13.29 | 1050.70 |
| 8 | 16.22 | 15.04 | 15.63 | 759.08 |
| 9 | 13.9 | 14.63 | 14.27 | 911.30 |
| 10 | 16.59 | 17.05 | 16.82 | 655.47 |
| AVG | | | | 899.46 |

Laboratory Technician:__________________

Page 1 of 1

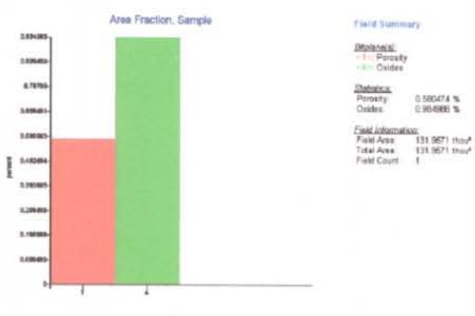
| FSI FLAME SPRAY INC. | Quality Control Microstructure Examination Report | Flame Spray Inc.<br>4674 Alvarado Canyon Rd.<br>San Diego, CA 92120<br>619-283-2007 |
|---|---|---|

| | | | |
|---|---|---|---|
| Work Order #: | 18668 | Application Spec: | AMS 2447 |
| Purchase Order #: | W9127N-10-Q-0002 | Lab. Technician: | Ricky Lee |
| Customer: | U.S. Army Green River Dam Project | Objective: | 200X |
| Material: | Stellite 21 Lot # 5090136-2 | Applicator: | Ricky T. |
| Date: | 11/24/09 | Sample Number: | 8T-A |

**Acceptance Criteria**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Cracks (None) | NONE | Porosity Max 2% | 0.58% | Interface Contamination No Delam. | Acceptable No Delam. | Oxide Max 1%__ | 0.98% |

| | | | |
|---|---|---|---|
| Unmelted Particles | Acceptable | Abrasive Particles | Acceptable |



# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



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30Jun2011

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Cavitation-Resistant Coatings for Hydropower Turbines

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
Ryan Sollars and Alfred D. Beitelman

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
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Champaign, IL 61826-1076

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**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

Operating hydropower turbines to obtain the ultimate power output often results in cavitation (the rapid formation and collapse of vapor pockets in a flowing liquid in regions of very low pressure) in the turbine area. The level of cavitation typically destroys organic coatings in a relatively short time. Traditional metallizing to repair cavitation damage has resulted in unsatisfactory performance. Other coating systems, such as those deposited by High Velocity Oxygen Flame (HVOF), have been laboratory tested and shown to hold promise but have not been evaluated in actual long-term field applications.

This study evaluated HVOF-applied coating systems that hold promise for long-term cavitation resistance and apply the most promising products to turbine areas for long-term field performance data. Work consisted of evaluating existing published and unpublished data on cavitation-resistant materials and selecting the most promising systems for field application. Those systems were then applied to areas of a turbine to evaluate their long-term performance.

After 1 year, it is clear that many of the coatings have failed. Two of the coatings, however, appear to be virtually unchanged from the time of application and may be found to provide long-term resistance to damage caused by cavitation.

**15. SUBJECT TERMS**
Cavitation, Hydropower turbines, Protective coatings

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | 19b. TELEPHONE NUMBER *(include area code)* |
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