FINAL REPORT

**HIGH PRODUCTIVITY
VACUUM BLASTING SYSTEM**

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LTC TELETRAK, Inc.

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EXECUTIVE SUMMARY

OBJECTIVE

The Department of Energy (DOE) needs improved technologies to decontaminate large areas of both concrete and steel surfaces. The technology should have high operational efficiency, minimize exposures to workers, and produce low levels of secondary waste. In order to meet the DOE's needs, an applied research and development project for the improvement of a current decontamination technology, Vacuum Blasting, is proposed. The objective of this project is to improve the productivity and lower the expense of the existing vacuum blasting technology which has been widely used in DOE sites for removing radioactive contamination, PCBs, and lead-based paint. The proposed work would increase the productivity rate and provide safe and cost-effective decontamination of the DOE sites.

SCOPE OF WORK

The Vacuum Blasting Technology has been successfully used for the decontamination of steel and concrete surfaces at nuclear facilities and at other installations. This technology can offer a safe, economical and efficient means for cleaning up hazardous materials from many different types of surfaces. Vacuum Blasting generates minimal waste (1% of conventional open sand blasting) and virtually no dust or emissions. However, the present equipment is not optimal for blasting productivity, and the physics of multi-flow in the system has not been well understood. Some areas that affect blasting productivity are the efficiency of nozzles, ergonomic handling of the blasthead, and recycling of the abrasive.

This work focuses on redesigning and improving existing vacuum blasting technology including blasthead nozzles, ergonomic handling of the blasthead by reducing its weight, brush-ring design, vacuum level regulator, efficiency of the dust separator, and operational control sensors. The redesign is expected to enhance the productivity and economy of the vacuum blasting system by at least 50 percent over current vacuum blasting systems. The actual cost of decontaminating a given area will, of course, be dependent upon the coating being removed, the shape of the surface, and the accessibility afforded to the operators of the vacuum blasting equipment.

There are three phases in the project. Phase I consists of developing and testing mathematical models. Phase II consists of pre-prototype design, fabrication, and pre-prototype unit testing. Phase III consists of prototype design and field verification testing.

In Phase I, mathematical models were developed and analyzed for the nozzle, blasthead, wind curtain, and dust separator, first as individual devices and then combined as an integrated model. This allows study of respective airflow and design parameters. The Contractor, based on the results of the mathematical modeling studies, designed experimental models of the components and tested these models. In addition, the Contractor developed sensors to detect the relationship of the blasthead to the blast surfaces and controls to minimize the dependency on an operator's skill and judgment to obtain optimum positioning, as well as real-time characterization sensors to determine as the blasthead is moving the depth to which coatings must be removed, thereby improving production and minimizing

waste. The Phase I work showed that the experimental results agreed with the numerical estimated data with a deviation within $\pm 10\%$, thus proving the mathematical model and model test successful. The tasks of Phase I were completed successfully and accepted by NETL.

In Phase II, the innovative components, including the blasting nozzle, the blasthead incorporated with sensors and wind curtain, and two separators, were designed and fabricated. All the newly designed components were tested at Contractor's site as individual devices and then in the integrated system. The pre-prototype unit testing was performed at FIU-HCET's Technology Assessment test facility. The demonstration for the pre-prototype and baseline technology were performed on coated steel plate and concrete wall under standard non-nuclear conditions. The coating on the concrete wall and steel plate was carefully selected for simulating the real contaminated surface at DOE facilities. The test of the radiological sensor was performed inside the lab with a simulated radiation source. In addition, the nozzle wear test was also performed for each nozzle to measure the nozzle lifetime. The Phase II work showed that the productivity rate was increased more over the baseline technology, 36% for the coated steel plate and 52% for the concrete wall, thus proving the pre-prototype design and test successful. The tasks of Phase II were completed successfully and accepted by NETL.

In Phase III, the Contractor designed and constructed the prototype of the High Productivity Vacuum Blasting System based on the research results of Phase I and II. Two blasthead prototypes, the dual centrifugal separator and the electronic control system with sensors were designed and constructed incorporated with LTC 1072 machine. The field verification testing of the prototypes were performed at FIU-HCET's test facility. The demonstration for the prototypes were performed on coated steel plate and concrete wall under standard non-nuclear conditions. For comparison, the coating on the concrete wall and steel plate was exactly same to that used in Phase II pre-prototype testing. The testing results indicated that the productivity rate of the standard blasthead prototype has been increased over 50% than that of baseline technology, and the productivity rate of the large blasthead prototype has been increased near 100% over that of the standard blasthead prototype. Therefore, the tasks of this project has been successfully completed and the goal of this project is achieved.

RESULTS AND MAJOR CONCLUSIONS

The prototypes of the High Productivity Vacuum Blasting System were designed and constructed based on the results of numerical modeling and pre-prototype testing performed on Phase I and Phase II. The verification testing of the prototypes was successfully performed at FIU-HCET's test facility.

The demonstration for the prototypes were performed on coated steel plate and concrete wall under standard non-nuclear conditions at FIU-HCET's test facility. The comparison of the prototypes developed in this project with the baseline technology was performed by removing the coating from the steel plate and concrete wall under the same conditions of coating. The standard technology assessment criteria were used to assess the prototype and baseline technology. The following tables list the description of surface media and test results:

Test surface and removal media description

ID No.	Removal Media Used	Demonstrated Surface Media	Size of Area Assigned	Test Surface Media Description	Demonstrated Geometry
1 (Standard blasthead)	80-grit	Carbon Steel	16 ft ²	Coated metal plate with an epoxy polyamine coating primer of 8 mils Ply-Mastic and 8 mils Ply-Thane 890 HS. 4x4x1/4" thick	Plate
2 (Standard blasthead)	80-grit	Concrete Wall	16 ft ²	Concrete-poured, with an epoxy polyamine coating primer of 7 mils Ply-Mastic and 1.5 mils Ply-Thane 890 HS. The coated concrete ceiling has the dimension of 4x4 with a compression strength between 4420 to 5660 psi.	Plate
3 (Large blasthead)	80-grit	Carbon Steel	16 ft ²	Coated metal plate with an epoxy polyamine coating primer of 8 mils Ply-Mastic and 8 mils Ply-Thane 890 HS. 4x4x1/4" thick	Plate
4 (Large blasthead)	80-grit	Concrete Wall	16 ft ²	Concrete-poured, with an epoxy polyamine coating primer of 7 mils Ply-Mastic and 1.5 mils Ply-Thane 890 HS. The coated concrete ceiling has the dimension of 4x4 with a compression strength between 4420 to 5660 psi.	Plate

Field verification test result

	Production Rate (ft ² /hr) Coated Steel Plate	Production Rate (ft ² /hr) Concrete Wall
The Redesigned Standard System (1/4 inch Blasthead)	16.0 (ID no.1)	40.0 (ID no.2)
Baseline Technology (1/4 inch Blasthead)	9.8	21.8
Increase of the Redesigned Standard System than Baseline Technology	63.3%	83.5%
The Redesigned Large Standard System (3/8 inch Blasthead)	33.8 (ID no.3)	74.0 (ID no.4)
Increase of the Redesigned Large System than Baseline Technology	245%	239%
Increase of the Redesigned Large System than the Redesigned Standard System	111%	85.0%

The major conclusions through the completion of this project include:

- The productivity rate of the standard blasthead prototype was increased more compared to the baseline technology, by 63.3% for the coated steel plate and 83.5% for the concrete wall; and the productivity rate of the large blasthead prototype was almost doubled compared to the standard blasthead prototype, increased by 111% for the coated steel plate and 85.0% for the concrete wall.
- Any of three materials (Boron Carbide, Tungsten, and Roctec 500) can be used to fabricate the blasting nozzle because the wear is so minimal and it can be ignored even after 10 hours of blast testing. The Boron Carbide being much lighter is the recommended one. The stainless steel is not suitable to fabricate the commercial nozzle because there are a little of considerable wearing near the throat area after one hour blasting.
- The developed vibration separator can successfully pre-separate the large, low-density particles created from the concrete wall; and both developed single and dual centrifugal separators can be used to separate the fine grits (G80 abrasives) from the dust without too much dust drops to the pressure vessel.
- The “lift-off” sensors designed can shut off the blasting operation when the blasthead is taken away from the cleaning surface; the radiological sensor can successfully detect the level of contamination on the surface and the control box and relative software can simultaneously control two types sensors for two blastheads.
- With the optimum configuration of the blasthead, air flow injection, and vacuum pressure, the air barrier created by the wind curtain can contain the abrasive within the blasthead and make the blasthead easy to move around on the cleaning surface.

As mentioned above, the productivity rate of the redesigned vacuum blasting system has been improved more than 50% over the baseline technology, also with high efficiency of the dust separator and less secondary waste, and with high safety and work efficiency because of the add-on sensors. Therefore, all tasks of this project have been successfully completed and the objective of this project has been achieved.

INTRODUCTION

The Department of Energy (DOE) needs improved technologies to decontaminate large areas of both concrete and steel surfaces. The technology should have high operational efficiency, minimize exposures to workers, and produce low levels of secondary waste. In order to meet the DOE's needs, an applied research and development project for the improvement of a current decontamination technology, Vacuum Blasting, is proposed. The objective of this project is to improve the productivity and lower the expense of the existing vacuum blasting technology which has been widely used in DOE sites for removing radioactive contamination, PCBs, and lead-based paint. The proposed work would increase the productivity rate and provide safe and cost-effective decontamination of the DOE sites.

The Vacuum Blasting Technology has been successfully used for the decontamination of steel and concrete surfaces at nuclear facilities and at other installations. This technology can offer a safe, economical and efficient means for cleaning up hazardous materials from many different types of surfaces. Vacuum Blasting generates minimal waste (1% of conventional open sand blasting) and virtually no dust or emissions. However, the present equipment is not optimal for blasting productivity, and the physics of multi-flow in the system has not been well understood. Some areas that affect blasting productivity are the efficiency of nozzles, ergonomic handling of the blasthead, and recycling of the abrasive.

This work focuses on redesigning and improving existing vacuum blasting technology including blasthead nozzles, ergonomic handling of the blasthead by reducing its weight, brush-ring design, vacuum level regulator, efficiency of the dust separator, and operational control sensors. The redesign is expected to enhance the productivity and economy of the vacuum blasting system by at least 50 percent over current vacuum blasting systems. The actual cost of decontaminating a given area will, of course, be dependent upon the coating being removed, the shape of the surface, and the accessibility afforded to the operators of the vacuum blasting equipment.

Recent research for the open blasting industry has shown that the performance of the nozzle can be improved in three ways: 1) run at the design nozzle pressure or above; 2) run the smallest feasible abrasive grit size; 3) use an improved blasting nozzle. Among these three, only the redesign of the nozzle offers an estimated 80 percent increase in efficiency. Work done recently has achieved an order-of-magnitude increase in the overall performance of blasting nozzles [1-2]. With a better understanding of the air-abrasive flow inside the nozzles as well as inside the blasthead, a better vacuum blasting nozzle should be developed.

The second task to be considered is the dust separator. Present operating experience with the LTC Vacuum Blasting Machine shows that the separation performance is not satisfactory for small size grit. Fine steel grit particles are useful for improving the cleaning production rate. However, such fine particles are easily entrained by the fine particles and the dust removed from the decontamination surfaces. This decreases the efficiency of the whole system. The dust separator will be redesigned or a secondary separator introduced based upon testing.

The new blasthead will also need to incorporate sensors for triggering shut-down if the blasthead is taken away from the surface and sensors to ensure neither "under nor over" cleaning of a given surface area by providing highly desirable real-time characterization to determine the effectiveness of decontamination. The sensors to meet such demands need to be developed.

This project will produce an innovative vacuum blasting system with the following advantages over existing technology: 1) An improved blasting nozzle, making vacuum blasting more efficient; 2) A more efficient dust separator, hence less secondary waste generation; 3) A novel blasthead design offering better ergonomics, more reliability, and less operator dependency. The entire project consists of three phases. Phase I develops and tests mathematical models and has been completed and accepted by NETL. Phase II consists of pre-prototype design and fabrication and pre-prototype unit testing which has been completed and accepted by NETL. Phase III consists of prototype design and field verification testing. This work has been completed and reported in the later sections. The main objective of this phase is to design and fabricate the prototype and test its performance, using an existing LTC machine as the base criterion. This report includes all the work performed in this project.

1. PHASE I - NUMERICAL MODELING AND MODEL TESTING

In Phase I, mathematical models were developed by FIU-HCET and used to analyze the nozzle, blasthead, wind curtain, and dust separator as individual devices and combined as an integrated model. Based on the modeling data, the innovative rectangular nozzle and a new centrifugal separator were designed, manufactured, and tested. The experimental results agreed with the numerical estimated data with a deviation within $\pm 10\%$, thus proving the mathematical model and the model test successful. In addition, both numerical predictions and model test results showed that the productivity and economy of the existing vacuum system could be increased by 50% if the new innovative key components replace the existing ones. Two types of blasthead sensor systems, a radiological characterization sensor system, and a lift-off sensor system also were developed. The radiological characterization sensor system minimizes the standoff distance from an adjacent perpendicular surface. The lift-off sensor system incorporates sensitive differential pressure switch/transducers to monitor the generated negative pressure within the blasthead.

1.1 NUMERICAL MODELING

1.1.1 Two-phase mathematical model

The fully three-dimensional air-particle two-phase model, incorporating some existing models, has been developed for simulating two-phase flow in the entire vacuum blasting system. The calculations were performed for the blasting nozzle, separator, and blasthead/wind curtain. The governing equations, turbulent models, and boundary conditions, etc., are described in detail in the following sections.

1.1.1.1 Governing equations for continuous phase

For the continuous phase (compressible air), the governing equations for conservation of mass, momentum, and energy can be written as follows:

Mass:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \quad (1)$$

Momentum:

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} + \frac{\partial p}{\partial x_i} = 0 \quad (2)$$

Energy:

$$\frac{\rho}{\rho} + \frac{\rho}{\rho} (u_j (e + p)) - \frac{\partial}{\partial x_j} (u_i \tau_{ji} + q_j) = 0 \quad (3)$$

With the assumptions of ideal air, the following additional equations can be added to correlate the governing equations.

State equation:

$$p = \rho RT \quad (4)$$

For energy e , we have

$$e = \frac{p}{\gamma - 1} + \frac{1}{2} (u_1^2 + u_2^2 + u_3^2) \quad (5)$$

Because the air velocity is not very high in some region of the vacuum blasting system, such as in separator and head of blasthead, the air can be considered as an incompressible fluid in those regions.

1.1.1.2 Turbulence models for continuous phase

The standard $k - \epsilon$ model was adopted in this study. This turbulence model contains the transport model equation considering the turbulent kinetic energy (k) and its dissipation rate (ϵ). The k equation was derived from the exact equation, while the ϵ equation was obtained using physical reasoning and bears little resemblance to its mathematically exact counterpart.

The turbulent kinetic energy, k , and its rate of dissipation, ϵ , were obtained from the following transport equations:

$$\rho \frac{Dk}{Dt} = \rho \left[\left(\mathbf{m} + \frac{\mathbf{m}}{\mathbf{S}_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k + G_b - \rho \epsilon - Y_M \quad (6)$$

and

$$\rho \frac{D\epsilon}{Dt} = \rho \left[\left(\mathbf{m} + \frac{\mathbf{m}}{\mathbf{S}_\epsilon} \right) \frac{\partial \epsilon}{\partial x_i} \right] + C_{1\epsilon} \frac{\epsilon}{k} (G_k + C_{3\epsilon} G_b) - C_{2\epsilon} \rho \frac{\epsilon^2}{k} \quad (7)$$

where G_k represents the generation of turbulent kinetic energy due to mean velocity gradients, G_b is the generation of turbulent kinetic energy due to buoyancy, Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, and $C_{1\epsilon}$, $C_{2\epsilon}$, and $C_{3\epsilon}$ are constants. $\mathbf{S}_k$ and $\mathbf{S}_\epsilon$ are the turbulent Prandtl numbers for k and ϵ , respectively.

1.1.1.3 Force balance equations for discrete phase

The discrete phase (particle) was simulated in a Lagrangian frame of reference. The discrete phase consisted of spherical particles dispersed in the continuous phase (air). The trajectory of the discrete phase particle was predicted by integrating the force balance on the particle, which was written in a Lagrangian reference frame. This force balance equated the particle inertia with the forces acting on the particle and can be written (for the x direction in Cartesian coordinates) as

$$\frac{du_p}{dt} = F_D (u - u_p) + g_x (\mathbf{r}_p - \mathbf{r}) / \mathbf{r}_p \quad (8)$$

where $F_D (u - u_p)$ was the drag force per unit particle mass and

$$F_D = \frac{18\boldsymbol{m} C_D \text{Re}}{\mathbf{r}_p D_p^2} \frac{1}{24} \quad (9)$$

where u is the fluid phase velocity, u_p is the particle velocity, $\boldsymbol{m}$ is the molecular viscosity of the fluid, $\mathbf{r}$ is the fluid density, $\mathbf{r}_p$ is the density of the particles, and D_p is the particle diameter. Re is the relative Reynolds number.

1.1.1.4 Discrete phase in turbulent flows

The dispersion of particles due to turbulence in the fluid phase is modeled using the stochastic discrete-particle approach. In this approach, the turbulent dispersion of particles is predicted by integrating the trajectory equations for individual particles, using the instantaneous fluid velocity, $\bar{u} + u'(t)$, along the particle path during the integration. Computing the trajectory in this manner for a sufficient number of representative particles may account for the random effects of turbulence on the particle dispersion. In this study, the Discrete Random Walk (DRW) model is used. In this model, the fluctuation velocity components are discrete piecewise constant functions of time. Their random values are kept constant over an interval of time given by the characteristic.

1.1.1.5 Performing trajectory of discrete phase calculation

In the uncoupled two-phase flow calculation, the following steps were performed:

- The continuous phase flow field was calculated.
- The discrete phase was introduced by computing the particle trajectories for each discrete phase injection.

1.1.1.6 Boundary conditions

There are two sets of boundary conditions. The first one is for the continuous phase (air); the second is for the discrete phase (particle).

For the continuous phase (air), a non-slip boundary condition was imposed on the wall. The total pressure, temperature, and static pressure were known at the nozzle entrance. At the nozzle exit plane,

all flow quantities were extrapolated from the two neighboring interior planes upstream of the exit plane. For separator and blasthead/wind curtain, the velocity inlet and pressure outlet boundary conditions were imposed on inlet and outlet plane.

For the discrete phase (particle), the available boundary conditions included the following:

“Reflect” indicates the rebound of the particle from the boundary in question with a change in its momentum being defined by the coefficient of restitution. For these computations, a coefficient of restitution equal to 0.0 implied that the particle retained none of its normal momentum after the rebound. A coefficient of restitution equal to 1.0 implied that the particle retained all of its normal momentum after the rebound (an elastic collision).

“Trap” indicates the termination of the trajectory calculations, and the fate of the particle is recorded as “trapped.”

“Escape” indicates the particle as having “escaped” when it encounters the boundary in question, thereby terminating trajectory calculations.

In this study, the following discrete phase boundary conditions were adopted:

- Inlet: “Escape”
- Outlet: “Escape”
- Wall: “Reflect,” a coefficient of restitution equal to 1.0

1.1.1.7 Particle physics properties

Two kinds of standard steel grits were adapted in this study: G40 with a particle size of 820 μm , and G80 with a particle size of 300 μm . Both have the specific gravity of 7.0 g/cm^3 .

The commercial software of FLUENT 5 was used as a solver to simulate the air-particle two phase flow for this project.

1.1.2 Numerical results and discussion (blasting nozzles)

1.1.2.1 Numerical results on the existing round nozzle

The calculations were performed with the fully three-dimensional model. The particle concentration distribution at the exit plane was obtained. Figure 1 shows the grid generation of the existing round nozzle with a throat diameter of 1/4 inch. Several cases for different inlet pressure have been run. When the nozzle inlet pressure was 100 Psi, the statistic average particle velocities on the exit plane of the nozzle were just 45m/s for G40 steel grit and 70 m/s for G80 steel grit, probably because the nozzle is too short to provide enough residence time for the steel grit in the nozzle. This is one of the major disadvantages.

The particle distribution at the exit plane of the nozzle is shown in Figure 2. When blasting, the steel particles were too concentrated, resulting in a narrow particle beam with a diameter of 0.46 inch (in a total circular area with a diameter of 0.72 inch). This is the second major disadvantage.

Figure 1. Multi-block structured grid of the existing round nozzle (the total cells are about 35,000).

Figure 2. Particles distribution at exit plane of the existing round nozzle.

1.1.2.2 Numerical results on the new rectangular nozzle

In this project, the new rectangular nozzle was proposed to overcome the disadvantages of the existing round nozzle. The geometry and grid system of the new rectangular nozzle is shown in Figure 3. Two kinds of rectangular nozzles with 1/4 and 3/8 inch hydrodynamic throat diameters were calculated for different lengths. The objective is to verify how the nozzle length affects the velocity and particle distribution and choose a suitable length. The theory is that increasing the nozzle length results in long resident time of the particles in the nozzle and increases the particle velocity. These cases are obtained

with the same conditions. Figure 4 shows the particle velocity at nozzle exit plane versus nozzle divergent length for $\frac{1}{4}$ and $\frac{3}{8}$ inch hydrodynamic throat diameter. A slop increase of the velocity with increasing the length is obtained when the divergent length is less than 8~10 inches. However, a slow increase trend is obtained when the length is larger than 8~10 inches. Such a trend is similar for both G-40 and G-80 particle grit.

Figure 3. Structured grid of the rectangular nozzle (total cells are about 35,000).

(a) $\frac{1}{4}$ inch size

(b) $\frac{3}{8}$ inch size

Figure 4. Particle velocities on the exit plane of the rectangular nozzle

The optimal geometry parameters of the rectangular nozzle were determined based on the above numerical results and from the practical application point of view.

1.1.2.3 Rectangular nozzle with 1/4 inch hydrodynamic throat diameter

With 1/4-inch hydrodynamic diameter, two nozzles with a 1/8 inch and a 3/16 inch flow passage thickness were calculated.

Nozzle #1

Dimensions:	Inlet cross plane	1 x 1 inch
	Throat cross plane	13/32 x 2/16 inch
	Outlet cross plane	23/16 x 2/16 inch
	Convergent length	2 inches
	Divergent length	6 inches
	Total Length	8 inches

Nozzle #2

Dimensions:	Inlet cross plane	1 x 1 inch
	Throat cross plane	17/64 x 3/16 inch
	Outlet cross plane	23/16 x 3/16 inch
	Convergent length	2 inches
	Divergent length	6 inches
	Total Length	8 inches

The difference between the above two nozzles exists in the flow passage thickness. One is 1/8 and the other is 3/16 inch, respectively. Table 1 illustrates the particle velocities for the two nozzles with grit G40 and G80 at inlet pressure of 100 Psi. It seems that the thickness does not affect the particle velocity more, and the velocities with fine grit G80 are always higher than those with coarse grit G40. Compared with the numerical results of the existing round nozzle at the same conditions (45m/s for G40 and 70m/s for G80), the statistic average particle velocities at the exit plane of the nozzle are increased more than 50%. Figure 5 shows the particle distribution at the exit plane of the rectangular nozzle. Both designs of the rectangular nozzle with hydrodynamic diameter of 1/4 inch was successful. From the practical view, Nozzle # 1 was consider as the optimum design for the rectangular nozzle of 1/4 inch size.

Table 1 The average particle velocities at the exit plane of the rectangular nozzle

	Nozzle #1	Nozzle #2
Particle: G40	67 m/s	62 m/s
Particle: G80	104 m/s	100 m/s

G40

G80

Figure 5. Particles distribution at exit plane of the nozzle (1/4 inch size).

1.1.2.4 Rectangular nozzle with 3/8-inch hydrodynamic throat diameter

The design objective of the large blasthead (3/8 inch size) is to double the productivity rate of the standard blasthead (1/4 inch size). For this purpose, two rectangular nozzles (Nozzle # 3 and Nozzle # 4) with hydrodynamic throat diameter of 3/8 inch were proposed to check the effects of nozzle length and outlet area on the nozzle performance. The major dimensions of these two rectangular nozzle are:

Nozzle #3

Dimensions:	Inlet cross plane	1 x 1 inches
	Throat cross plane	7/16×1/4 inch
	Outlet cross plane	13/8× 1/4 inch
	Convergent length	2 inches
	Divergent length	6 inches
	Total Length	8 inches

Nozzle #4

Dimensions:	Inlet	1 x 1 inches
	Throat	7/16 ×1/4 inches
	Outlet	2.0 ×1/4 inches
	Convergent length	2 inches
	Divergent length	8 inches

Total Length   10 inches

At the inlet pressure of 100 Psi, for G80 grits, the particle average velocities on the exit planes is 102 m/s for the Nozzle # 3 and 113 m/s for Nozzle # 4. Figure 6 showed the particle distribution on the exit planes of two rectangular nozzles. In Figure 6, the inside rectangle indicated the exit plane of Nozzle # 3, and the outside rectangle indicated the exit plane of Nozzle # 4. The numerical results showed the particle distribution was uniform for both nozzles; the average particle velocity of Nozzle # 4 was increased by 10.8% compared to that of Nozzle # 3 nozzle.

Figure 6 Particle distribution at the exit plane of the rectangular nozzles.

The optimum parameters of the rectangular nozzle with 3/8 inch hydrodynamic throat diameter was determined base on the information gathered from the numerical results of Nozzle # 3 and # 4 and the practical application point of view. The major dimensions of this rectangular nozzle were:

Number #5

Dimensions:	Inlet	1 x 1 inches
	Throat	14/32 x 1/4 inches
	Outlet	5/2 x 1/4 inches
	Convergent length	2 inches
	Divergent length	8.5 inches
	Total Length	10.5 inches

The numerical calculation was performed to verify the performance of this rectangular nozzle. Similar as the above two rectangular nozzle, at inlet pressure of 100 Psi, the average velocity of the particles on the nozzle exit plane was 113 m/s for G80 grit. Figure 7 showed the particle distribution on the exit planes of this rectangular nozzle; and the numerical simulation of particle trajectory colored by particle velocity inside the rectangular nozzle is shown in Figure 8.

The calculated results showed that the particle velocity was high (113m/s) and the particle distribution was uniform on the exit plane rectangular nozzle (see Figures 7 and 8). Thus, the design of the rectangular nozzle with hydrodynamic diameter of 3/8 inch was successful.

Figure 7. Particle distribution on the exit plane of the rectangular nozzle (3/8 inch size).

Figure 8. Numerical simulation of the particle trajectory inside the rectangular nozzle (3/8 inch size).

All of the above results were obtained at the ideal boundary condition: the inlet pressure was fixed at 100 psi, the wall of the nozzle was smooth, and the particles were considered as spherical, etc.

1.1.3 Numerical results and discussion (dust separators)

1.1.3.1 Numerical results of the existing separator

In order to determine the performance of the existing separator, numerical simulations have been carried out. The geometry and air flow field of the existing separator is illustrated in Figure 9. In this case, the inlet boundary conditions were set at 10m/s for the average air velocity. Two-dimensional calculation was performed with incompressible flow assumption. Non-uniform, unstructured grids were chosen, and almost 20,000 elements were used to discretize the computation domain. Results show that the air flow is concentrated in the center of the cylinders. This pattern reflects the influence of the inserted inclined plates. Therefore, the result is reasonable based on the fluid mechanics. It is estimated that the relative concentrated air flow may bring some particles out of the separator during the separating process. The calculated results of the separation efficiency can prove the above conclusion. Under this condition, the separation efficiency is about 90% for steel grit G40, but it is just about 27% for steel grit G80. Therefore, the centrifugal separator that replaces the existing one is needed when using finer steel grit.

Figure 9. The geometry and air flow field of the existing separator.

1.1.3.2 Numerical results of the new centrifugal separator

Numerical modeling was performed to investigate the air flow field, particle trajectory, and collection efficiency. The inlet boundary condition is set to 10 m/s for the average air velocity. Fully three-dimensional calculations are performed with incompressible flow assumption. Non-uniform, unstructured grids are chosen to discretize the entire computation domain.

Figure 10 was the schematic particle trajectories and grid system of the new centrifugal separator Figure 11 shows the air flow field in two symmetrical planes ($x=0$) and ($y=0$). The air flows down first, then turns to the exit of the separator due to the vacuum force. It is estimated that this air flow can entrain some small-sized particles out of the separator. Some large particles or heavy particles are collected in the bottom of the separator.

Figure 10. The schematic particle trajectories in the new designed centrifugal

Figure 11. Air flow field on two symmetrical planes of the centrifugal separator.

Figure 12 shows the influence of a separator's geometry on separation efficiency. First, with the increase of separator outside diameter, the separation efficiency increases. When the efficiency reaches the maximum value, it decreases with the outside diameter. Finally, the outside diameter that can provide the best separation efficiency is chosen for the new separator's outside diameter, i.e., 6 inches.

In this case (the outside diameter is 6 inches), the calculated separation efficiency is about 70% for steel grit G80. Compared with the existing separator, the separator efficiency for steel grit G80 was almost double. Therefore, the new centrifugal separator can separate the finer grit well; of course, it can separate the coarse grit. The numerical results of efficiency for two types of separator are listed on Table 2.

Table 2. Comparison of the efficiency of two separators

	Existing separator	New centrifugal separator
Efficiency (steel grit G40)	90%	
Efficiency (steel grit G80)	27%	70%

Figure 12. Outside diameter versus efficiency of centrifugal separator.

1.1.4 Numerical results and discussion (wind curtain)

The wind curtain is expected to have two functions. One is to create an air barrier to prevent the particles escaping to the atmosphere. The other is to make the blasthead float on the wall surface and

balance the forces. To achieve the above goals, a draft proposal is presented that is expressed in Figure 13.

Because the wall surface can not be very smooth, a gap between the wall surface and the blasthead was considered. The injected air has a fixed pressure, and the geometry has an inclined angle. The numerical modeling was performed to study the air flow field for the wind curtain. For the air injection system, the channel gap and the channel inclined angle are the main parameters. They are important parameters to affect the force balance within the whole system. The numerical modeling has been performed to obtain the optimal gap and the incline channel angle. The blasthead working distance is also an important parameter.

Three channel gaps of the wind curtain, of 1/16, 1/8 inch, and 1mm, were chosen for numerical modeling. The CFD modeling was conducted for each channel gap with 30°, 45°, and 60° inclination angles. The assumed working distances are from 0.1 to 3 inch. In these calculations, the injection pressures are fixed to be 1.2 ~ 3.0 bar and the vacuum pressure is set as 0.2 bar. One of the calculation cases on the air flow field in the wind curtain is shown in Figure 14. With an increase of injection pressure, the wind curtain efficiency can increase to almost 100% at some specific working distances. Therefore, the proposed wind curtain will be able to meet the desired need.

The lift force can also be balanced. The criteria of the optimum parameters are based on calculated results and a practical view. Under the conditions that the injection pressure is below 1.5 bar, the vacuum pressure is above 0.2 bar, and more than 95% of G80 grit will be contained inside the wind curtain, the calculated results provide the following optimal parameters: the channel gap is 1mm to 2mm; the incline angle is 45° to 60°; the working distance is less than 1 inch.

Figure 13. Proposed geometry of wind curtain.

Figure 14. Air flow field on the proposed wind curtain (gap=1/16 inch, angle = 60°, working distance = 0.25 inch).

1.2 MODEL TESTING

The objective of this report is to present the experimental results on the blasting nozzle and the new centrifugal separator, as well as the comparisons with CFD modeling. A flow loop, with air-particle two-phase flow has been set up. Combined with the LTC Vacuum Blasting Machine, the facilities have been successfully running. With the Phantom High-Speed Video Camera system, the particle velocity and their concentrations are measured, for both the existing circular nozzle and the new rectangular nozzle of ¼ inch diameter. The measurements matched the CFD modeling well, with the maximum distinction below 10.0%. A 6060P Pitot probe from ALNOR INSTRUMENT COMPANY was employed to obtain the velocity distribution. The comparison of experimental data and CFD modeling results showed that the design of the new centrifugal separator was successful.

1.2.1 Experimental results and their comparison with CFD modeling on the nozzle

1.2.1.1 Description of setup

Figure 15 illustrates the layout of the experimental setup. The LTC Vacuum Blasting Machine has been used to produce the blasting air-particle two-phase flow and the vacuum pipeline will be used to recycle the steel grit. As shown in Figure 15, the air compressor generates the high-pressure air. The high-pressure air is divided into three pipelines. Pipeline 1 is connected to the vacuum generator to produce vacuum. Pipeline 2 is connected to the pressure vessel. The air flow from pipeline 2 controls the valves (inside the pressure vessel) so that the steel grit can be drained from the upper chamber to the lower chamber in the pressure vessel. Of the three pipelines, pipeline 3 is the most important one. This pipeline produces the air-particle two-phase flow when the air is mixed with the steel grit that is drained from the lower chamber of the pressure vessel (see Figure 15). The air flow rate and the temperature are measured before the air is mixed with the grits.

1.2.1.2 Working mechanism

The air-particle two-phase mixture flows through the blasting nozzle. At the exit of the nozzle, the steel grit particles have a higher velocity. Between the blasting nozzle and the collection box, there is a rectangular glass channel (1×1 ft) with a length of 2 ft, through which the steel particles pass as a high-speed jet. The collection box collects the steel grit from the nozzle. This collection box is connected with the vacuum pipeline that is used to recycle the grit, after transporting the grit particles in the machine (see Figure 15).

1.2.1.3 Instruments

Three instruments are installed in pipeline 3 to measure the air flow rate, air temperature, and air pressure, as illustrated in Figure 15. The Phantom v3.0 High Speed Digetor Motion Analysis System is used to measure the steel grit velocity and the steel grit concentration in the experimental setup. The complete Phantom system includes three major components: a high-speed camera, pulsed laser source,

and PIV software. This system is the combination of a high-speed imager, capturing several thousand images per second, with the short duration sheet lighting formed by pulsed laser, that allows us to create sharp, clear pictures of a cross-sectional area of the flow. Since the pulsed duration of the laser (and hence the exposure time per image) is only 30 nanoseconds, the pictures will be sharp and blur-free to facilitate the measurements. After an image is complete, the PIV software is used to do particle tracking, auto or cross-correlation.

Figure 15. Experimental setup of particle velocity and concentration measurement of the blasting nozzle.

Figure 16 illustrates the measurement mechanism of the particle velocity and concentration. The nozzle produces the high speed air-particle jet along the x coordinate. Y is the vertical coordinate. The pulsed laser creates a vertical laser sheet with very short time duration and separation. Because the environment is “dark,” the moving particles can only be captured when the laser is on. The first dot is created on the image when the first laser pulse arrives. Continuously the second dot will be produced when the second laser pulse comes. The time difference between the first and the second laser pulse is defined as the time separation. For the present measurement, the particle velocity is very high; thus, short time separation is needed. The experiments show that it is suitable to choose the time separation of

25 μ s. Four laser pulses create four dots in the image, and the total time is $3 \times 25 \text{ ns}$. The following simple expression is used to calculate the particle velocity:

$$v = \frac{d \times 10^{-3}}{3 \times 25 \times 10^{-6}}$$

The units of d and v are mm and m/s, respectively.

Next is particle concentration measurement. Through data processing of the image file, two lines, lines AB and CD, can be identified to cover all particle dots in the image. Extending the two lines to the nozzle exit plane obtains the line EF, which is identified as the length of the particle coverage in y direction. For the circular nozzle, EF is the circular diameter that the particles cover at the nozzle exit plane. For the rectangular nozzle, two measurements are conducted: one with long side (EF) at horizontal position, and the other with long side (EF) at vertical position. Through data processing, the covering area of the particles at the exit plane can also be obtained.

Figure 16. Measurement mechanism of the particle velocity and concentration.

Figure 17 shows the measurement arrangement for the existing circular nozzle with $\frac{1}{4}$ inch throat diameter. Only one arrangement is needed due to the symmetry. Figure 18 show the two measurement arrangements for the new rectangular nozzle, which were mentioned above. For the present application, the duration and the separation are chosen to be 5 μ s and 25 μ s. The main part of the practical experiment setup for the blasting nozzle test is shown in Figure 19.

1.2.1.4 Test section

Two test sections were used. One is the existing round nozzle, and the other is the new rectangular nozzle. For the circular nozzle, the length of the convergent section is 1.68 inches, and the divergent

section possess the length of 2.18 inches. The new rectangular nozzle has the gap of 1/8 inch. The lengths of the convergent section and the divergent section are 2 and 6 inches, respectively. The equivalent diameter at the throat location is 1/4 inch. Compared with the classical circular nozzle, the new rectangular nozzle is a longer nozzle.

Figure 17. Measurement arrangement for the existing circular nozzle with 1/4 inch throat diameter.

Figure 18. Measurement arrangement for the new rectangular nozzle with long side at horizontal (left) and (right) position.

Figure 19. The test section for measuring blasting nozzle velocity and construction.

1.2.1.5 Experimental results and comparison with CFD modeling

Excellent image files were acquired, and the test cases are listed in Table 3.

Table 3. Six test cases

Nozzle	Test Pressure, Psi	Nozzle Arrangement
Circular Nozzle	65	See Figure 17
Circular Nozzle	83	See Figure 17
Rectangular Nozzle	65	With long side at horizontal position, see Figure 18
Rectangular Nozzle	82	With long side at horizontal position, see Figure 18
Rectangular Nozzle	65	With long side at vertical position, see Figure 18
Rectangular Nozzle	82	With long side at vertical position, see Figure 18

Because the conditions of the model test have some difference from that on the numerical calculation at the above section, the numerical simulation was carried out again under the model test conditions. Table 4 gives the information on the comparison of the measurements with the CFD modeling at the same conditions and the magnitude of velocity is a statistic average magnitude.

Table 4. Comparison of the measurement results with CFD modeling data

Nozzle	Pressure, psi	Velocity, m/s (measurements)	Velocity, m/s (CFD modeling)	Deviation
Circular nozzle	65	48.8	54	10.0%
Circular nozzle	83	58.3	64	9.8%
Rectangular	65	82.1	91	9.9%
Rectangular	82	112.0	101	10.0%

As evidenced in Table 4, the deviation of the experimental results from the modeling data is within $\pm 10\%$. Therefore, the model chosen for the numerical simulation was correct. Figure 20 is one of the typical particle imaging from the experimental process of the rectangular nozzle at different flow pressure. This figure also show that the particles almost fill in the rectangular nozzle blasting area. Therefore, the rectangular nozzles work efficiently.

**Figure 20. Particles imaging for rectangular nozzle at
P =65 psi (nozzle orientation, see Figure 18).**

1.2.2 Centrifugal separator test results

1.2.2.1 Efficiency test

The test of the new separator's separation efficiency was carried out for the same working conditions as the nozzles test (see Figure 21). The experiment procedure was as follows.

First, the new separator was fed by two kinds of dust obtained from the existing separator. The two kinds of dust were classified as concrete dust and coating dust. Second, the new separator's dust and recycle grit, which were collected with plastic bags, were weighed. The two different working conditions produced the following results:

1. For concrete wall surface, we obtained 84.1% recycle grit from the dust of the existing separator (a total of 796.4g dust was fed to the new separator. We got 126.4g pure dust and 670.5g recycle grit.). The efficiency of the existing separator for this condition was 25%.
2. For coating on steel plate surface, we obtained 73.5% recycle grit from the dust of the existing separator (90.5g dust was fed to the new separator. We got 24.0g pure dust and 66.5g recycle grit.). The efficiency of the existing separator for this condition was 30%.

The above results prove the almost doubled efficiency and the improved separation efficiency to perfect status.

Similar to the blasting nozzle, the numerical simulation was carried out on the centrifugal separator again at the model test condition. Compared with the experimental result of this centrifugal separator, the difference between numerical and experimental results is below $\pm 10\%$ (75% from numerical modeling data for this case; 84.1% and 73.5% from experimental results mentioned above). Table 5 lists all the comparison results.

Table 5. Comparison of the measurement results with CFD modeling data

	Efficiency (CFD modeling)	Efficiency (test data)	Deviation
Existing separator	27%	25% (for concrete surface)	5%
		20% (for coating on steel plate surface)	10%
Newly designed centrifugal separator	75%	84.1% (for concrete wall surface)	10%
		73.5% (for coating on steel plate surface)	5%

1.2.2.2 Velocity Distribution Test

In order to verify the modeling results, two different positions were chosen to obtain the new separator's internal velocity distribution. The experimental procedure is reported below.

Two ½ inch holes were drilled on the external surface of the separator. One is 2" and the other is 6" from the separator's top surface. The holes are on the opposite side surface of the separator's tangential air inlet channel. Two directional (tangential direction along the cylinder surface and axial along the vertical direction) velocities were measured to compare with the numerical simulation results. A 6060P Pitot probe from ALNOR INSTRUMENT COMPANY was employed to obtain the velocity distribution.

Figure 21 is a picture of the new centrifugal separator. In the picture, two probe holes, sealed with tape, can be seen clearly. Figures 22 to 25 show the results from experimental and numerical modeling. The direction of coordinates begins from the centerline of the separator to the air inlet channel surface. For the upper hole, since it was in the middle of two concentric cylinders, the distance is much shorter than that for the other position. Judging from these figures, the distinction of the experimental results and the estimated data agree fairly well with a deviation within $\pm 10\%$. Therefore, it can be assumed that the numerical model and the newly designed separator are successful.

Figure 21. Picture of the new centrifugal separator.

Figure 22. Comparison of numerical results and experiment data in the axial direction at the upper position (i.e., 2" to the separator's top surface).

Figure 23. Comparison of numerical results and experiment data in the tangential direction at the upper position (i.e., 2" to the separator's top surface).

Figure 24. Comparison of numerical results and experiment data in the axial direction at the lower position (i.e., 6" to the separator's top surface).

Figure 25. Comparison of numerical results and experiment data in the tangential direction at the lower position (i.e., 6" to the separator's top surface).

1.3 PHASE I SUMMARY

1.3.1 Conclusion of Phase I

Based on the proposed plan, Phase I has been fulfilled successfully. The main conclusions are as follow:

- The model tests for nozzle and separator have been performed successfully. The comparisons of model test data for blasting nozzles and the new centrifugal separator have been done. The maximum deviation from the experimental results for the modeling data is within $\pm 10\%$. This proves that the mathematical models for simulating air-particle flow in the vacuum blasting system are successful.
- The numerical modeling on blasting nozzles, including 1) circular and rectangular configuration; 2) the existing separator and newly designed centrifugal separator; and 3) the newly designed blasthead/wind curtain, has been finished as plan.
- The preliminary designs of the rectangular blasting nozzle, new centrifugal separator, and blasthead/wind curtain have been finished, based on numerical results.
- The experimental system for the test of particle speed and separator efficiency has been set up. The high-speed video camera system used to measure the particle velocity and concentration has been installed. All the instruments, including pressure gauge, flow meter, thermocouples, and Pitot probe, have been employed in the experimental process.
- The fabrications of the blasting nozzle with $\frac{1}{4}$ inch hydrodynamic throat diameter, collection box, centrifugal separator, and some other equipment have been done.
- Two types of sensor have been proposed. The radiological characterization sensor system will be incorporated into the structure of the blasthead as compactly as possible to minimize the stand-off distance from an adjacent perpendicular surface. The lift-off sensor system will incorporate sensitive differential pressure switches/transducers to monitor the generated negative pressure within the blasthead.

1.3.2 Lesson Learned

- The model testing showed that the centrifugal separator is too high and in not very stable incorporated with LTC 1060Pn machine. The geometry and parameters should be optimized in Phase II.
- The concept design of the wind curtain will need to be verified and optimized by experimental testing in Phase II.

2. PHASE II – PRE-PROTOTYPE DESIGN AND TESTING

In Phase II, the preliminary design of the components of the proposed system based on the information gathered in Phase I was preformed. This effort included an overall configuration of the system including: material selection and testing, definition of the range of dimensional and weight parameters, conceptual arrangement or design of the blast head unit, and dust separator unit. Based on the preliminary design, we procured components, and perform fabrication and assembly of the proposed system, and assembled and tested subsystems individually.

2.1 PRE-PROTOTYPE DESIGN AND FABRICATION

2.1.1 Blasting Nozzle

2.1.1.1 Design of Blasting Nozzle

Based on the numerical results and practical view, the new rectangular nozzle in which the hydrodynamic diameter of the throat is $\frac{1}{4}$ inch has been designed for the prototype of standard blasthead pre-prototype. The flow passage dimension of the rectangular nozzle dimensions are obtained from the numerical results, as shown in Table 6. The design of the nozzle insert is shown in Figure 26, the detail design drawings are presented in Appendix A. The thickness of the nozzle insert is $\frac{3}{16}$ inch.

Table 6. The flow passage dimensions of the rectangular nozzle ($\frac{1}{4}$ inch hydrodynamic throat diameter)

Description	Dimensions (inch)
Length of the divergent section	6
Length of the convergent section	2
Width of the inlet cross-section	1
Thickness of the inlet cross-section	1
Thickness of the divergent section	$\frac{1}{8}$
Width of the exit plane	$\frac{23}{16}$

Figure 26. The design drawing of the rectangular nozzle (1/4 inch size).

2.1.1.2 Material Selection

Since the nozzle is the most wearing part of the entire blasthead, the selection of the nozzle material is a very important issue. The literature research, which focused on the friction duration of material, was performed to select the material suitable for the new rectangular nozzle. Based on the literature research and practical view, three materials were selected to fabricate the nozzle inserts. They are Tungsten Carbide, Boron Carbide, and Roctec 500. The wear test for these materials was also performed.

2.1.1.3 Fabrication of Blasting Nozzle

Figure 27 shows a photo of the nozzle insert and its housing for the standard blasthead pre-prototype. The nozzle inserts made of Boron Carbide and Tungsten consist of four pieces, two pieces for the convergent section and two pieces for the divergent section. For the nozzle inserts made of Roctec 500, the divergent section consists of four pieces due to manufacturing issues. Thus, the nozzle inserts made of Roctec 500 consist of six pieces.

Figure 27. The nozzle insert and housing for the standard blasthead

2.1.2 Blasthead

The blasthead consists of blasting nozzle, vacuum system, wind curtain, and some connection components. Numerical simulation and experimental test had been done on the major components of the blasthead, namely, blasting nozzle, wind curtain, and interface of blasting and vacuum system. The design of the standard blasthead pre-prototype was shown in Figure 28. This blasthead has been designed with the analysis of numerical simulation results. The configuration of this blasthead is that the grits hit the cleaning surface at 45° angle and dust and grits are vacuumed at 90° degree. The advantage of this configuration is to maximize the grits' blasting force so as to obtain the high productivity rate.

Figure 28. The pre-prototype of the standard blastehead

Figure 29 shows the standard blastehead pre-prototype made of aluminum alloy. The wind curtain will be formed with injection compressed air through three hollow screws on the top of the blastehead, as shown in Figure 29. The cover of the nozzle insert was designed for connecting two parts so as to open easily for checking the wear of the nozzle.

Figure 29. The pre-prototype of the standard blastehead

2.1.3 Design of Dust Separator

2.1.3.1 Vibration Separator

Since the nozzle shape changed from a round to a rectangular channel, the nozzle's cross-section became a narrow and long rectangular channel. Because of this, the channel is easily blocked when the system is operational, especially when cleaning concrete surfaces. Therefore, we designed a new vibration pre-separator for larger particles with low density. The principal section of this pre-separator is a plastic tube with a sieve held in vertical position. A hammer is employed to hit the plastic tube frequently to disengage the large particles blocked by the sieve. The large particles will drop into the collection box. The new separator is easy to fix and remove from the operating system to accommodate different working conditions and purposes. Figure 30 presents the final design drawings of the pre-separator which incorporated with LTC 1060Pn machine. The detailed design drawings are presented in Appendix B.

Figure 30. The design drawing of the single vibration separator.

The single vibration separator was designed for separating the large, low-density particles under the separator from the concrete cleaning surface for LTC 1060Pn machine, as shown in Figure 31.

Figure 31. The single vibration separator

2.1.3.2 The Centrifugal Separator

Figure 32 depicts the design drawing of the centrifugal separator for LTC 1060Pn machine. Based on the model testing results, the major dimensions of the centrifugal separator were optimized, especially for reducing the height of the separator. This centrifugal separator can reach the previous separation efficiency (from 73.5% for coating on steel plate surface to 84.1% for concrete wall surface) and will be more stable. The detailed design drawings of the centrifugal separator are listed in Appendix C.

Figure 32. The design drawing of the single centrifugal separator.

The redesigned centrifugal separator for separating the fine grits from the dust for LTC 1060Pn machine was shown in Figure 33.

Figure 33. The single centrifugal separator

2.1.4 Design of Sensors

2.1.4.1 "Liftoff" Sensors

The idea of the liftoff sensors is to maintain safe operations at all times. Unsafe operation could be the result of operator error or machine malfunctions. The liftoff sensor system was designed to account for failures "in itself." In other words, if one of the sensors is disconnected, the blasthead will not operate. Also without power, or with a failed air solenoid, the blasthead will not operate.

The proximity sensors were selected for the liftoff detection sensors because they can detect all of the surfaces that are going to be decontaminated by the LTC system. Capacitive sensors were chosen over inductive sensors because they will detect a surface at approximately twice the distance for sensors of the same diameter. In other words the detection distance is doubled without increasing the size of the detector. The particular supplier of proximity sensors was chosen because they have solid state electronics to improve reliability and all the electronics are filled with an epoxy type of potting compound to improve their resistance to high vibrations. The model of proximity sensor was picked to be shielded to be more noise-tolerant, and a DC open collector output was picked for ease of use.

2.1.4.2 Radiological Sensor

The radiological sensors are needed to detect the level of contamination on the surface being cleaned. Two sensors are used to monitor the contamination level in real time. One sensor is always over the unclean surface to show its radioactivity prior to cleaning. This knowledge in real time can help the operator know how much blasting is needed on a particular area before cleaning it. A second sensor, located 180 degrees from the first on the blasthead, is used to check contamination of the most recently blasted area. This lets the operator know in real time if they have cleaned the contaminated area to a safe level. The radiation controls consist of 5 LEDs (Light Emitting Diode), 2 LED bargraph displays, and two pushbuttons.

For the design of the electronics, a microcontroller was used. A microcontroller allows easy design changes in the future and has a quicker initial design time than using analog circuit design. The Motorola 68HC16 microcontroller was chosen because it has all the necessary I/O built in and was fast enough to perform all necessary processing real-time. The I/O used on the microcontroller were two PWM (Pulse Width Modulation) channels, 9 digital output lines, 1 RS232 port, and 4 external interrupt lines. The PWM outputs provide (through an RC filter) the 0-1 volt DC to control the LED bargraph displays. They are basically being used as digital to analog converters. The 9 digital output lines are used to control the 5 LEDs. Four extra lines are needed since 4 of the 5 LEDs are 2 colors.

The software programmed into the embedded microcontroller uses all of the hardware described above to get and give feedback to the user. It also uses two radiation detectors to collect radiation data. Figure 10 shows the operation of the embedded software. You can see there are two software loops. One loop is a standard loop in which the 'main' function is run and initialization is performed. Once the system is initialized, the 'main' function only prints debugging output to the RS232 port. The other loop is where interrupts are processed. Interrupts occur when a button is pressed, at a set time (possibly every 1 ms), and when radiation is detected.

2.1.4.3 Fabrication of sensors

Pictures of proximity sensor with LED and radiological sensor are shown in Figures 34 and 35. They are used for safe operations and detect the level of contamination on the surface being cleaned. Figure 36 shows the electronic control box for the two types of sensors.

Figure 34. The proximity sensor.

Figure 35. The radiological sensor.

Figure 36. The electronic control box.

2.2 PRE-PROTOTYPE TESTING

2.2.1 Blasting Nozzle

As mentioned earlier, to ensure the expected lifetime of the nozzles, three materials, Tungsten Carbide, Boron Carbide, and Roctec 500, were chosen for fabricating nozzles. For each nozzle, a 10 hours' blasting test was performed to measure their wear. The test time for the other components that needed the nozzle blasting was accumulated to the total blasting time. For the nozzle wear test, the blasthead was fixed on one thick steel plate. During the test process, the blasting was stopped each hour to check the conditions of blasthead and the steel plate.

The following three methods were used to measure the wear of the nozzle:

Weight method. The status of nozzle wear can be obtained from the weight lost before and after the lifetime test. The parameters used in the method follow.

The volume of the nozzle inserts is 4.38 inch³. The inside surface area is 5.53 inch². The material densities are Boron Carbide, 2505 kg/m³; Tungsten Carbide, 14500 kg/m³; Roctec 500, 15545 kg/m³. The average depth loss of the nozzle inside can be obtained by calculating the nozzle weight loss. Table 7 lists the weight loss of three nozzle inserts.

Table 7. The weight loss on the nozzle wear testing

Nozzle Material	Initial Weight (Before test)	Final Weight (After test)	Weight loss
Boron Carbide	178.96 g	178.52 g	0.44 g
Tungsten	1041.75 g	1041.72 g	0.03 g
Roctec 500	1115.92 g	1115.41 g	0.51 g

As shown in Table 7, the weight loss for the three nozzle inserts is less than 1g after ten hours of blasting.

Visualization method. The wear of the nozzle inside can be observed if the wear is even minor. For these three nozzle materials, the wear of nozzle inserts is too little to be seen after 10 hours.

Local depth measurement. The local depth of the nozzle inside was measured by using a three-dimensional coordinate system. The initial data of the three nozzles were obtained by measuring the local coordinates of the nozzle inside before the blasting test and used as the basic criteria. After the blasting test, the local coordinates of the nozzle insert were measured again and compared with the initial data. The comparisons indicated that the difference in the nozzle surface change falls in the error range of the

machine. So there is no wear that can be measured with this method. This conclusion agrees with that of the weigh method.

As evidenced by the above data, the three materials are good for fabricating the nozzle insert. Based on our test results, after 10 hours blasting, there just exists tiny wear that hardly can be observed by our current methods. Among the three materials, the Boron Carbide is the best because its weight is just 1/5 of the other two material nozzles.

2.2.2 Wind Curtain

In the pre-prototype testing, two different hoses, which connected the air drier to blasthead with diameters of 3/8 inch and 1/2 inch respectively, were used to provide injection air for wind curtain. The wind curtain was formed by injecting compressed air through three even hollow screws of 1/4 inch. The test indicated that the hose with 1/2 inch diameter was better than that of 3/8 inch diameter for wind curtain performance alone. In addition, the test results showed that the air barrier formed by the wind curtain could not contain all the abrasive within the blasthead. Then, a temporary ring was fixed on the top of the blasthead to prevent the abrasives escape outside of the blasthead. It was found that the wind curtain incorporated with the ring could make the blasthead float on the surface and contain the abrasives inside the blasthead.

The reasons why the previous design did not work well were that 1) the pressure loss on the hose was considerable so that the injection pressure of the wind curtain was not high enough; 2) the speed of the rebound abrasives was too high because the abrasives hit the surface with high speed at a direction of 45 degrees. Therefore, further modification of the geometry of the wind curtain and the use of a much higher injection pressure will be needed.

2.2.3 Dust Separators

2.2.3.1 Vibration Separator

The primary test of the vibration separator was performed at FIU-HCET. The sieve with 2mm mesh chosen from three mesh sizes (1mm, 2mm, and 2.8mm) was used in the pre-separator. When the G80 steel grit is used as the cleaning media, the test results showed that the pre-separator could work well for separating the large-size particles (no big particles were found in the blast system after checking the pressure vessel and blasthead). The test results also show that under this working condition, the pre-separator can continue to work for more than five hours. Then the sieve in the pre-separator should be cleaned because some particles with sizes almost the same as the mesh size can choke it.

2.2.3.2 The Centrifugal Separator

In order to measure the efficiency of the centrifugal separator, samples from the loop were analyzed. Recycled grits on the pressure vessel were collected in a plastic bag. Then these recycled grits were separated using the sieve (0.15 mm size). New G80 grits were separated with the same sieve. For the new G80 grits, the grits with size less than 0.15 mm is 6.5% (50g/770g); for the recycled G80 grits, grits with size less than 0.15 mm is 12% (99g/820g). The difference between new grits and recycled

grits is 5.5%. Since the recycled grits have been used for more than 10 hours (just this time), it seems that not much dust drops to the pressure vessel.

The "generation of steel dust" was collected in the drawer during the blasthead lifetime test. A thick steel plate was used to do blasting. After one hour blasting, only about 2 inch x 1/4 inch mark (about 5 mm deep) can be seen in the steel plate. Therefore, there is not much dust in the drawer. After 5 hours testing, only 1.6 pounds of dust are in the drawer. This compares very favorably with the baseline technology. Tests [3] have demonstrated production of dust, even with much coarser steel grit abrasives (G25/40LO & G25/40) of 1 to 1.8 lb/hr, and unpublished test results of even 3.5 lbs/hr. It should also be compared to the used of non-recyclable abrasive, such as sand, which would produce approximately 500 lbs per hour [4].

2.2.4 Sensors

2.2.4.1 "Liftoff" Sensors

The testing of the liftoff sensors was done to ensure that they would perform as desired. By their specifications, the sensors did what was needed to detect liftoff. Testing needed to be done to make sure they actually could detect liftoff under all desired conditions.

The liftoff sensor itself is a fairly simple capacitive proximity sensor that either detects the surface or it doesn't. It is capable of detecting if a surface is below the blasthead or not, and doing so at 100 Hz. In other words, the maximum time it will take the sensor to detect a liftoff condition is 1/100th of a second. The sensing of materials is based on the dielectric of a material. The selected sensors can detect materials with dielectrics of 1.5 or greater. The sensitivity of the sensors can be adjusted to change what dielectric can be detected and at what distance.

The three needed proximity sensors were powered by a 12 VDC supply, and they were tested with various materials in the lab to determine their effectiveness in detecting materials. The sensors have a small red LED that lights up when an object is detected. This LED was used for testing purposes in the lab. Objects such as steel plates and concrete were used to test the maximum detection distance and the effects of adjusting the sensors on that distance. For these tests, all the sensors performed better than their specifications. Table 8 shows the collected data.

Table 8. Proximity sensor detection distances

Pot (turns past max sensitivity)	Initial detection (mm) (CCM1-1808N)	Released detection (mm) (CCM1-1808N)	Initial detection (mm) (CCM1-1204N)	Released detection (mm) (CCM1-1204N)	Material
"0"	12.7	25.4	6.35	7.9375	brick
"1/8"	9.5	12.7	3.175	3.175	brick
"1/4"	6.4	9.5	1.5875	3.175	brick
"3/8"	6.4	9.5	N/a	N/a	brick
"1/2"	3.2	3.2	N/a	N/a	brick
"5/8"	1.6	1.6	N/a	N/a	brick
"0"	12.7	25.4	6.35	7.9375	concrete
"1/8"	9.5	7.9	3.175	3.175	concrete
"1/4"	6.4	9.5	1.5875	3.175	concrete
"3/8"	6.4	9.5	N/a	N/a	concrete
"1/2"	3.2	3.2	N/a	N/a	concrete
"5/8"	1.6	3.2	N/a	N/a	concrete
"0"	12.7	25.4	6.35	7.9375	steel
"1/8"	9.5	7.9	3.175	3.175	steel
"1/4"	6.4	9.5	1.5875	3.175	steel
"3/8"	6.4	9.5	N/a	N/a	steel
"1/2"	3.2	3.2	N/a	N/a	steel
"5/8"	1.6	3.2	N/a	N/a	steel
"0"	9.5	25.4	1.5875	12.7	wood
"1/8"	4.7	7.9	1.5875	3.175	wood
"1/4"	6.4	4.7	0.79375	1.5875	wood
"3/8"	3.2	6.4	N/a	N/a	wood
"1/2"	3.2	3.2	N/a	N/a	wood
"5/8"	1.6	3.2	N/a	N/a	wood

In the next stage of testing, all the sensors were mounted on the blasthead. A circuit to use all three sensors and detect a liftoff condition was designed and used. The circuit works on the principle that if one of the three sensors doesn't detect a surface below it, then liftoff has occurred. A time delay of approximately 100 ms was included to prevent the blasting from switching off and on rapidly on rough surfaces.

The blasthead with the three proximity sensors and the liftoff detection circuit were taken outside for testing. Surfaces that are expected to be encountered and available were tested. These surfaces include steel plates, cylindrical steel tubes (as might be encountered as pillars), smooth concrete, and rough concrete. The testing was done on all the surfaces by moving the blasthead along the surfaces and making sure no false liftoff conditions were detected. If a liftoff was detected while the blasthead was operating over these surfaces, the extra switching on and off of the blasting could shorten the lifespan of the system. It could also prove to be an annoyance, where individuals in the field would seek a way to bypass the sensors altogether. This would then become a concern for the safety of operation. During all of the testing on the mentioned surfaces, no false liftoff conditions were detected.

During this testing, the sensors were adjusted to their most sensitive position. To improve response time, the sensors could be adjusted based on the surface on which they are being used. For instance, on the rough concrete, moving the blasthead approximately 1/4" off the surface would trigger the liftoff condition. On the other hand, this distance was closer to 1/2" on the smooth concrete. This is important because this effects the total response time of the liftoff detection circuit. It would also allow the blasthead to be operated while not on the surface, degrading system performance.

To complete testing, the liftoff detection circuitry was used while the blasthead was in operation. Tests were done to make sure that faults were failsafe and no false liftoff conditions occurred. The blasting stopped when the electronics were unplugged, one or more sensors were disconnected, the air hose was disconnected, or the air solenoid wiring was disconnected. This simulated a real-world fault with the system and proved that blasting would stop with a system fault. During several hours of operation, no false liftoff conditions were detected. This proved the reliability of the system.

2.2.4.2 Radiological Sensors

The radiological sensor chosen was a scintillation probe type 41 from Dosimeter. It has a usable energy range of 20 keV to 2 MeV. The crystal is 19 mm by 25 mm and is in a lead cylindrical shield to reduce background count by about 4 times. The probe is not sensitive to alpha radiation and is opaque to β with energies below 1 MeV.

The probe was directly connected to a high voltage supply/pulse detector that was commercially available. The chosen detector was the Aware Electronics PMI-30. It meets all the needs of this application and allows adjustment of both the high voltage and the threshold voltage. This makes it possible to change the radiological sensor by simply readjusting the high and threshold voltages.

To verify the performance of the PMI-30/type 41 combination, several tests were run. The tests were done with four different radiation sources and at three different source-to-detector distances. The results are shown in Table 9. The tests were all done after a minimum of 5 minutes prior operation before testing. This time was used to let the electronics settle.

Table 9. Detection efficiency of type 41 probe

Distance	Sr-Y-90	Cesium 137 (2)	Cesium 137 (3)	Cobalt 60
2 cm	835	926	106687	892
2 cm	795	905	106120	930
2 cm	778	863	106407	923
2 cm	776	666	106113	886
2 cm	735	845	106715	890
5 cm	669	819	40601	714
5 cm	594	811	40827	701
5 cm	626	872	40586	703
5 cm	643	827	40668	686
5 cm	668	807	40463	688
10 cm	664	675	18022	658
10 cm	652	716	18186	626
10 cm	617	727	17900	709
10 cm	639	711	17925	655
10 cm	621	658	18165	657
Bgnd AVG	256	256	256	256
2 cm AVG	784	841	106408	904
5 cm AVG	640	827	40629	698
10 cm AVG	639	697	18039	661

The sources used for the tests are standard sources used for calibrating radiation probes. The Sr-Y-90 is a beta standard, while the Cs-137 (Cesium) and Co-60(Cobalt) are gamma standard sources. The Sr-Y-90 has maximum energy of 0.54 and 2.26 MeV. Because the second released beta is above the 1 MeV that the type 41 probe detects, it was used to test the beta efficiency of the probe. Cs-137 emits .661 MeV gamma with a yield of 85%, while Co-60 emits gamma of 1.17 and 1.33 MeV.

Testing of the radiological sensor system has been done to the extent possible with current resources. For further testing, the complete system would need to be operated in a contaminated area that was in need of decontamination. Testing in this fashion would guarantee proper operation in field conditions. As it stands, the only source of radiation is in sources and not on surfaces that could be cleaned. This future testing would show that the system could detect changes in radioactivity in real-time without any unforeseeable problems. For testing to be considered 100% complete, this final testing needs to be done.

2.2.5 Pre-prototype unit testing

2.2.5.1 Description of the Experimental Setup

The pre-prototype unit testing was performed at FIU-HCET's site. The experimental setup mainly consisted of the air compressor rented from Kelly Tractor Co., air dryer and LTC 1060Pn machine made by LTC Teletrak Inc. The LTC 1060Pn is designed as a high-capacity direct pressure blasting machine featuring a continuous blast media feed system. This feature allows the machine to be kept compact and lightweight but with a minimum down-time for media and machine handling. For the pre-prototype unit testing, some modifications had been done on the air dryer and LTC 1060 Pn machine. Figures 37 also show these modifications. As shown in Figure 37 (left), a valve was installed on the air dryer in order to get the injection air for the wind curtain. The gauge was used to measure the air pressure and flow rate. Figure 37 (right) also shows the LTC 1060Pn machine with the new centrifugal separator and the replaced vacuum generator. The new design blasthead incorporated with "liftoff" sensor and wind curtain are shown in Figure 38 (left). The complete electronic control box for sensors and blasthead trigger is shown in Figure 38 (right).

Figure 37. The modified air dryer (left) and LTC 1060 machine (right)

Figure 38. The redesigned blasthead (left) and electronic control box (right)

The demonstration of the pre-prototype system was performed on coated steel plate and concrete wall. The coating of the steel plate consisted of an epoxy polyamine coating primer of 8 mils Ply-Mastic and 8 mils Ply-Thane 890 HS. The coating of concrete wall consisted of an epoxy polyamine coating primer of 7 mils Ply-Mastic and 1.5 mils Ply-Thane 890 HS.

2.2.5.2 Experimental Results and Discussion

The pre-prototype unit testing was performed for cleaning the coated steel plate and concrete wall by using the redesigned vacuum blasting system and baseline technology. Table 10 lists the test case.

Table 10. Test surface and removal media description

ID No.	Removal Media Used	Demonstrated Surface Media	Size of Area Assigned	Test Surface Media Description	Demonstrated Geometry
1 (New)	80-grit	Carbon Steel	4 ft ²	Coated metal plate with an epoxy polyamine coating primer of 8 mils Ply-Mastic and 8 mils Ply-Thane 890 HS. 4x4x1/4" thick	Plate
2 (New)	80-grit	Concrete Wall	4 ft ²	Concrete-poured, with an epoxy polyamine coating primer of 7 mils Ply-Mastic and 1.5 mils Ply-Thane 890 HS. The coated concrete ceiling has the dimension of 4x4 with a compression strength between 4420 to 5660 psi.	Plate
3 (Baseline)	40-grit	Carbon Steel	4 ft ²	Coated metal plate with an epoxy polyamine coating primer of 8 mils Ply-Mastic and 8 mils Ply-Thane 890 HS. 4x4x1/4" thick	Plate
4 (Baseline)	40-grit	Concrete Wall	4 ft ²	Concrete-poured, with an epoxy polyamine coating primer of 7 mils Ply-Mastic and 1.5 mils Ply-Thane 890 HS. The coated concrete ceiling has the dimension of 4x4 with a compression strength between 4420 to 5660 psi.	Plate

The test results are listed in Table 11.

Table 11. Test Results

	Production Rate (ft²/hr) Coated Steel Plate	Production Rate (ft²/hr) Concrete Wall
Redesigned System (NEW)	13.3 (ID no.1)	33.2 (ID no.2)
Baseline Technology	9.8 (ID no.3)	21.8 (ID no.4)
Increase of Redesigned System than Baseline Technology	36%	52%

As shown in Table 11, for the coated steel plate, the productivity rate of the redesigned system was increased by 36%. And for the concrete wall, the productivity rate of the redesigned system was increased by 53%. The main reasons affecting the productivity rate of the pre-prototype are 1) the new

blasthead is heavy and cumbersome and not user-friendly because it is designed as testing model; 2) the operator is hard ergonomically to handle the new blasthead due to its heavy weight. The test results indicated that the redesigned system worked well and almost meet the design goal. Of course, further modification will be needed to improve the performance of the pre-prototype system.

2.3 PHASE II SUMMARY

2.3.1 Conclusion of Phase II

Based on the proposed plan, Phase II has been fulfilled successfully. The main conclusions are as follow:

- The pre-prototype unit testing has been performed at FIU-HCET's Technology Assessment site. The whole redesigned vacuum blasting system works successfully for cleaning the different media surfaces. The productivity rate and the economy of the redesigned system were increased almost 50% over the baseline technology.
- New materials, Tungsten Carbide, Boron Carbide, and Roctec 500, used to manufacture the liner to the rectangular blasting nozzle all test were satisfactorily, but the Boron Carbide being much lighter is the preferred one.
- Two separators, the pre-separator designed for large, low-density particles created by cleaning the concrete wall and the centrifugal separator designed for separating the fine grits from the dust, have been designed and fabricated, and their separation efficiencies have been measured. The test results show that the two separators can work well as expected. The separation efficiency of the centrifugal separator for the G80 grits was almost double that of the old one.
- The radiological sensors and their electronic control system were tested by using the simulated radiation source in the lab. The result indicated the design of the rad sensor and its electronic control system was successful. The rad sensor can efficiently detect the level of contamination on the surfaces.
- The "liftoff" sensor system consisted of three proximity sensors and the electronic control system. It was designed to incorporate with the blasthead. Both the lab test and on-site test indicated this system can shut off the trigger successfully when the blasthead is taken from the surface, as expected.
- The blasthead incorporated with sensors and wind curtain has been designed, fabricated, and tested. The test showed that the production rate of the vacuum blasting system can be increased much more when the blasthead pre-prototype was used.

2.3.2 Lesson Learned

The information about how to improve the performance of the redesigned system has been obtained from this pre-prototype unit testing. The following issues need to be considered in the final design of the prototype as follows in Phase III:

- Although the productivity rate of the blasthead pre-prototype has been increased much more, its configuration makes the wind curtain hard to retain the abrasives within the blasthead. Therefore, the configuration of the blasthead pre-prototype should be modified for the wind curtain performance.

- The test results shows that the blasting nozzle angle should be further optimized to a more vertical position. The brush ring will be helpful for the operation.
- The size of the pre-separator can be further reduced for better operation.

3. PHASE III - PROTOTYPE FIELD VERIFICATION TSETING

In Phase III, the design of a prototype of the High Productivity Vacuum Blasting System was developed based on the results of Phase II.. The proposed system unit was a full-scale prototype unit. The integrated vacuum blasting system design was reviewed and problems identified in the pre-prototype testing corrected to optimize the working relationship between the various components of the system. Based on the prototype unit design, FIU-HCET procured components, and performed fabrication and assembly of the proposed system. The Field Verification Testing for the prototype was carried out at FIU-HCET's Technology Assessment Site. A number of individual tasks were tested. The purpose of this test is to verify the performance of the newly designed vacuum blasting system.

3.1 PROTOTYPE DESIGN

3.1.1 Design of Blasting Nozzles

The pre-prototype testing indicated that the design of the ¼ inch size nozzle was successful. Thus, the ¼ inch size nozzle designed on Phase II is used on the prototype design, see Table 6. Similar as the ¼ inch size nozzle, the new rectangular nozzle in which the hydrodynamic diameter of the throat is 3/8 inch has been designed for the large blasthead prototype. The flow passage dimension of the rectangular nozzle dimensions are obtained from the results of numerical simulation, as shown in Table 12. The design of the nozzle insert is shown in Figure 39. The thickness of the nozzle insert is 3/16 inch. The 3/8 inch nozzle inset was made of stainless steel because of the tight timeframe and it will be only used for a short time test.

Table 12. The flow passage dimensions of the rectangular nozzle (3/8 inch hydrodynamic diameter)

Description	Dimensions (inch)
Length of the divergent section	8.5
Length of the convergent section	2
Width of the inlet cross-section	1
Thickness of the inlet cross-section	1
Thickness of the divergent section	0.25
Width of the exit plane	2.5

Figure 39. The nozzle insert for the large blasthead

3.1.2 Design of Blasthead

The blasthead consists of blasting nozzle, vacuum system, wind curtain, and some connection components. Numerical simulation and experimental test had been done on the major components of the blasthead, namely, blasting nozzle, wind curtain, and interface of blasting and vacuum system. The design activities of the entire blastheads are discussed in the following sections. The detailed design drawings of the entire blasthead are presented in Appendix A. Two blastheads are designed in this project, one is the standard blasthead prototype (1/4 inch size), another is the large blasthead prototype (3/8 inch size)

3.1.2.1 The Standard Blasthead

The testing results of the pre-prototype indicated that the productivity rate of the pre-prototype has been increase much more than the baseline technology. In addition, this test results showed that the air barrier formed by the wind curtain could not contain all the abrasive within the blasthead because the speed of the rebound abrasives was too high, and also it is not user-friendly configuration.

To overcome this problem, the additional testing was performed to select the appropriate blasting angle. Three different blasting angles (85 °, 90 °, 95 °) and one vacuum angle (45 °) were tested. The test results indicated that the productivity rate of the blasthead with vertical blasting were increased, as compared to that of the blasthead pre-prototype. Therefore, the vertical blasting angle was considered as the best choice.

The optimum configuration of the 1/4 " blastheads has been determined based on the test results of the trial blastheads. The configuration of the standard blasthead prototype was same to that of the LTC standard blasthead. Namely, the blasting nozzle is in the center of the blasthead at a vertical direction, and the vacuum will surround the blast tube. In addition, both wind curtain and brush ring will be used in the final design of the blasthead prototype. Figure 40 showed the design of the standard blasthead prototype (1/4 inch size). The prototype mainly consists of nozzle insert, nozzle housing, cylindric tube blasthead shell, and brush ring & wind curtain. In the above components, the outside shell is same as

that used in the existing standard blasthead. Four holes are used to distribute the injection air for the wind curtain.

Figure 40. The prototype of the standard blasthead and its components

3.1.2.2 The Large Blasthead

The design of the large blasthead prototype was shown in Figure 41. Similar as the standard blasthead prototype, the outside shell of the existing large blasthead is used in the new large blasthead. On the large blasthead, there are six hollow screws used to distribute the inject air for the wind curtain, three shelves used to plug the “lift-off” sensors, and one shelf used to plug the radiation sensor.

Figure 41. The prototype for the large blasthead and its components

3.1.3 Design of Dust Separator

3.1.3.1 The Dual Vibration Separator

Figure 42 showed the design of the dual pre-separator for the LTC 1072 machine. The detailed design drawing are presented in Appendix B. This device consists of two independent pre-separators that can work simultaneously. The configurations of these two pre-separators are similar to that developed in Phase II for the LTC 1060Pn machine.

Figure 42. The design drawing of the dual vibration separator

3.1.3.2 The Dual Centrifugal Separator

The new dust separator was proposed for the LTC 1072 machine. This separator will consist of two centrifugal separators that can work simultaneously, as shown in Figure 43. This new separator will replace the existing separator on the LTC 1072 machine for separating the fine grits from the dust. The configurations of these two centrifugal separators are similar to those developed in Phase II for the LTC 1060Pn machine. The specific dimensions for these two centrifugal separators were determined by empirical calculations.

The detailed design drawing were presented in Appendix C. According to the calculation for centrifugal design, the centrifugal separator's configuration is different for nozzle dimensions of 1/4" and 3/8". The centrifugal separator for 3/8" nozzle is larger than that for 1/4". In order to meet the need for these two kinds of nozzles, a middle configuration dimension is used for the designation. That is, the centrifugal separator's size is 1.4" larger than that for 1/4" nozzle but smaller than that for 3/8" nozzle.

Figure 43. The design drawing of the dual centrifugal separator

3.1.4 Design of Sensors

The LTC monitoring system is used for getting instant readings on contamination removal. It was developed by FIU-HCET using two detectors with two blastheads to survey the contamination before and after blasting. The counts from the detectors are recorded in on-board computer and monitored in a screen visible to the operator.

The electronics components of the LTC monitoring system consist of:

Tow high voltage 900 volts pulse detector

Precision signal counter module

Miniature 100 MHz 486 based computing module

Active matrix flat panel display

Data collection and display rate 0.55 sec/count

Hard drive 850 MB

Floppy drive

Keyboard

Lift-off sensors on/off switch

Trigger switch

Each module is controlled by a custom software application developed by HCET.

Figure 44 depicted the LTC monitoring system. Figure 45 showed the control box block diagram. Figure 46 and 47 showed the circuit schematics of LTC monitoring system.

Figure 44. LTC monitoring system.

3.1.4.1 Radiological sensor

The probe is a thin end window gas proportional, which detects alpha, beta, and gamma radiation. A removable, cleanable grill protects the mica window, which has dimensions of 2 cm diameter x 1.5 mg/cm². The primary use of the probe is to locate surface contamination. Its dimensions are: 2" of outside diameter x 7.7" long. The sensor has a weight of 750 grams, and operates at 900 v DC.

The sensor is used in conjunction with the controller to indicate the level of contamination with respect to a known level. Also indicates the effectiveness of the cleaning in real time.

Table 13. Data obtained from the radiation detector

Background	Alpha AM241-23a	Beta SRY-90	Gamma CS 137
3	37	1071	2038
6	36	1045	2177
3	31	1063	2174
5	33	1152	2232
9	34	1170	2303
Notes: All units are in counts per second. Time is constants at 30 seconds. Distance from the probe to the radiation source is 2 cm.			

3.1.4.2 Proximity sensors

Proximity sensors are designed to function at different sensing distances varying from 1 mm to 30 mm. The proximity sensors chosen for this project are from HTM Electronics Industries and have a sensing distance of 4 mm to 8 mm. The 100 Hz sampling rate makes the sensors very rapid in responding to the change in blasthead to wall distance. In fact, it is the 1-second of time for the mechanical pinch valve to operate that limits system shutdown with removal of blasthead from the wall.

The proximity sensor used a pinch-off valve to cut the flow to the blasthead when ‘lift-off’ condition occurs. Also prevents ineffective cleaning while blasthead is in ‘lift-off’ condition.

3.1.4.3 Control box

The control box is designed for two blastheads. This box has two points on opposite side where sensors are to be connected. The main on/off switch is located on the front side of the control box, where the floppy drive unit is provided. The lift-off sensor has two switches; one is located on the box and the other, at the blasthead. This allows the operator to turn it off manually in case of a sensor failure. Each blasthead has two normally open valves, one is to trigger the unit and the other is to stop the flow to blasthead, although this procedure is optional.

To operate the LTC control box, the first step is to connect valves, sensors and power lines according to their corresponding labels. Once this is done, the main power switch should be turn on and the operator should proceed to verify that the fan in the control box is working. Then, the operator will wait for instructions on the screen.

3.1.4.4 System Software

To control the system the next options are provided on the software:

Calibration: No calibration is required for this application.

Begin Monitoring: To ensure that the background count is very low.

Not to exceed 100 CPS in a non-radioactive area.

File Transfer: To capture and saved data in floppy disks.

Set time: To set the time.

Date: To set the date.

Exit: Exit the system software.

Figure 45. Control box block diagram

Figure 46. Circuit schematics

Figure 47. Circuit schematics

3.2 PROTOTYPE FABRICATION

The fabrication of the prototypes, for which the design activities were mentioned in above, are discussed in the following sections. Among these components, the nozzle inserts of the standard blasthead prototype were ordered from an outside workshop with FIU-HCET providing the design drawing. The others were fabricated in the FIU-HCET machine shop. The detailed pictures of all the new fabricated components are shown in Appendix D.

3.2.1 Blasting Nozzle and Housing

Figure 48 shows a photo of the nozzle insert and its housing for the large blasthead prototype. The nozzle inserts were made of stainless steel and consisted of four pieces, two pieces for the convergent section and two pieces for the divergent section. The nozzle insert for the standard blasthead prototype was same to that used in Phase II pre-prototype, see Figure 27.

Figure 48. The nozzle insert and housing for the large blasthead

3.2.2 Dust Separators

The dual centrifugal separator was designed for separating the fine grits from the dust for LTC 1072 machine which two independent blastheads can work simultaneously, as shown in Figure 49.

Figure 49. The dual centrifugal separator

3.2.3 Sensors

Pictures of proximity sensor and radiological sensor are shown in Figures 50 and 51. They are used for safe operations and detect the level of contamination on the surface being cleaned. Figure 52 and 53 shows the electronic control box and monitoring for the two types of sensors.

Figure 50. The proximity sensor

Figure 51. The electronic control box

Figure 52. The electronic control box

Figure 53. Monitoring screen

3.2.4 Blastheads

The standard blasthead prototype was shown in Figure 54. The configuration of the prototype for the standard blasthead is similar to that of the LTC standard blasthead. The components of this prototype are made of aluminum. Except for the outside shell which is the same to used in the LTC standard blasthead, the other parts are newly designed and fabricated. Four hollow screws are used to distribute the injection air for the wind curtain.

Figure 54. The prototype of the standard blasthead

Figure 55 shows the prototype of the large blasthead (3/8 inch size). Similar as the standard blasthead, the outside shell of the existing large blasthead is used in the prototype. On the large blasthead, there are six hollow screws used to distribute the inject air for the wind curtain, three shelves used to plug the “lift-off” sensors, and one shelf used to plug the radiation sensor.

Figure 55. The prototype of the large blastehead

3.3 PROTOTYPE TESTING

3.3.1 Trial blasthead testing

3.3.1.1 Trial Blasthead

In order to investigate the influence of different blasting angles on productive rate, the standard blasthead pre-prototype developed in Phase II was modified to use the different blasting and vacuum angles. The vacuum angle of the trial blasthead was kept at constant at 45° , and the blasting angles were chosen at 85° , 90° , and 95° respectively. In addition, the brush ring and plastic ring were fabricated to be incorporated into the trial blastheads for comparison. The fabrication of the above test model was done at FIU-HCET. Figure 56 (left) shows the blasthead at vertical blasting direction with steel brush ring and other two connected pieces, which were used to form 85° and 95° blasting angles. Figure 56 (right) also shows the head of blasthead with hard ring, which was the same as used in Phase II's test. The body of blasthead was made of aluminum. The brush ring was made of steel, and the hard ring was made of plastic.

Figure 56. The trial blasthead at the vertical 90° blasting direction and two connected pieces for blasting angles of 85° and 95° with brush ring (left) and plastic hard ring (right).

3.3.1.2 Experimental Results and Discussion

The experimental setup for the pre-prototype testing described as above was used to perform the trial blasthead testing. The purpose of the test for the trial blasthead was to select the appropriate blasting angle. The selection criteria were production rate, and wind curtain performance, as well as the “user-friendliness” nature of the operation. For these purposes, systematic tests were performed by cleaning coated flat steel plate and concrete wall. The coatings on both the steel plate and concrete wall were exactly the same as that used in Pre-prototype tests. The cleaning area is 2 ft² for the each case. G80 grit was used as the removal media in this test. Table 14 listed the test results of the trial blasthead at different conditions.

Table 14. Test Results for Trial Blastheads

Production Rate (ft ² /hr)	Blasthead (Blasting at 90°)		Blasthead (Blasting at 85°)		Blasthead (Blasting at 95°)	
	Plastic ring	Brush ring	Plastic ring	Brush ring	Plastic ring	Brush ring
Coated Steel Plate	28.8	30.0	24.0	30.4	27.2	30.4
Concrete Wall	40.0	45.0	41.6	45.0	41.6	48.0

The major results of the above tests are as follows:

- The average production rate of the new-trial blasthead was increased by 80%, as compared to that of the preprototype blasthead, developed in Phase II. The major reason was that the new trial blasthead, by delivering the abrasive in a vertical direction, results in the abrasive being more easily sucked back by the vacuum air flow. There is no overlapping of the abrasive blasting travelling to the cleaning surface, and the removal of the “spent abrasive” by the vacuum air flow. Therefore, the vertical blasting angle was the best choice. The test results of the new-trial blastheads re-emphasized that the goal to increase the productivity of the vacuum blasting system, by at least 50% over current baseline vacuum blasting technology, can be achieved.
- The retention of abrasive in the new-trial blastheads, was markedly better than that experience during the Phase II testing of the blasthead pre-prototype.
- The blasthead with brush ring worked better than that with hard ring because the former can move smoothly on both steel plate and concrete wall. The performance of wind curtain was also improved as compared to the Phase II tests. The blasthead was easy to move and “user-friendly” to operate.
- The trial blastheads with all three blasting angles (85°, 90°, 95°) worked well, with similar production rates. But, because of its greater ease of fabrication, the vertical blasting angle (90°) is recommended for the prototype design.

- In summary, the optimum configuration of the blasthead is one with the vertical blasting angle, incorporating the brush ring and wind curtain.

3.3.2 Field verification testing

3.3.2.1 Description of the Experimental Setup

The field verification testing was performed at FIU-HCET's site. The test system setup for the verification testing had been set up. This system mainly consisted of the air compressor, CD 1300 air dryer and LTC 1072 machine made by LTC Teletrak Inc. For the prototype verification testing, some modification had been made on the air dryer and LTC 1072 machine. Figure 57 shows the LTC 1072 machine with the new dual centrifugal separator and the air dryer with an additional valve and outlet for providing the injection air for wind curtain. Figure 58 shows the LTC sensor and its control system which can control triggers and sensors for the two blastheads simultaneously.

Figure 57. The modified air dryer (left) and LTC 1072 machine (right)

Figure 58. The control box and monitor of the sensor system

Figure 59. The standard blasthead prototype (left) and large blasthead prototype (right)

The standard blasthead and large blasthead prototypes are shown in Figure 59. The demonstration of the redesigned vacuum blasting system was performed on coated steel plate and concrete wall which the exactly same to that used in the pre-prototype testing.

3.3.2.2 Experimental Results and Discussion

Blasting Nozzle

The large nozzle inserts was made of the stainless steel. After one hour blasting, there was a little bit of wearing on the diverging section of the inserts (two parts). There was one wearing area of 0.37" (wide) x 1.95" (long) which start from the throat section on the diverging section. The wearing range is 0.1mm ~ 0.2mm thickness.

Wind Curtain

The following modifications were made on the prototype to improved the wind curtain performance:

- The configuration of the prototype for standard blasthead was changed, similar as that of the existing LTC standard blasthead
- Both wind curtain and brush ring were used in the prototype of the standard blasthead
- To use the large diameter hose (one inch) to transport the injection air for the wind curtain
- To adjust the blasting and vacuum pressure on the LTC machine for acquiring the maximum vacuum capability.

With the above modifications, the abrasives escaping from the blasthead have been significantly reduced to minimum and acceptable level. The performance of the wind curtain has been much improved. The working principle of the wind curtain of the large blasthead prototype is the same as that of the standard blasthead prototype, and functions efficiently.

Dust Separators

The dual centrifugal separator works well for the LTC 1072 machine. There are almost no useful abrasives can been seen in the dust box. The separator efficiency of the dual centrifugal separator can be reached as that of the singular centrifugal separator. The average production of dust for coated steel plate and concrete wall is about 1.5 lb/hr.

Prototype verification testing

The field verification testing was performed for cleaning the coated steel plate and concrete wall by using the prototype of the vacuum blasting system. Table 15 lists the test case.

Table 15. Test surface and removal media description

ID No.	Removal Media Used	Demonstrated Surface Media	Size of Area Assigned	Test Surface Media Description	Demonstrated Geometry
1 (Standard blasthead)	80-grit	Carbon Steel	16 ft ²	Coated metal plate with an epoxy polyamine coating primer of 8 mils Ply-Mastic and 8 mils Ply-Thane 890 HS. 4x4x1/4" thick	Plate
2 (Standard blasthead)	80-grit	Concrete Wall	16 ft ²	Concrete-poured, with an epoxy polyamine coating primer of 7 mils Ply-Mastic and 1.5 mils Ply-Thane 890 HS. The coated concrete ceiling has the dimension of 4x4 with a compression strength between 4420 to 5660 psi.	Plate
3 (Large blasthead)	80-grit	Carbon Steel	16 ft ²	Coated metal plate with an epoxy polyamine coating primer of 8 mils Ply-Mastic and 8 mils Ply-Thane 890 HS. 4x4x1/4" thick	Plate
4 (Large blasthead)	80-grit	Concrete Wall	16 ft ²	Concrete-poured, with an epoxy polyamine coating primer of 7 mils Ply-Mastic and 1.5 mils Ply-Thane 890 HS. The coated concrete ceiling has the dimension of 4x4 with a compression strength between 4420 to 5660 psi.	Plate

The test results are listed in Table 16. As shown in Table 16, for the coated steel plate, the productivity rate of the prototype of the standard blasthead was increased by 63.6%. And for the concrete wall, the productivity rate of the prototype of the standard blasthead was increased by 83.5%. Compared to the prototype of the standard blasthead, the productivity of the prototype of the large blasthead was increase 111% for the coated steel plate, and 85.0% for the coated concrete wall. The main reason the productivity rate of the prototype of the large blasthead is the temporary shelf is used to support the large blasthead, replace of the LTC Floor Trolley. Therefore, it is difficult to operate the prototype of the large blasthead, especially on the concrete wall because its surface is rough. With the help of the LTC Floor Trolley, the performance of the prototype of large blasthead can be significantly increased. Thus, the productivity rate of the prototype for the large blasthead can be definitely expected to double that of the prototype for the standard blasthead.

Table 16. Verification test results

	Production Rate (ft²/hr) Coated Steel Plate	Production Rate (ft²/hr) Concrete Wall
The Redesigned Standard System (1/4 inch Blasthead)	16.0 (ID no.1)	40.0 (ID no.2)
Baseline Technology (1/4 inch Blasthead)	9.8	21.8
Increase of the Redesigned Standard System than Baseline Technology	63.3%	83.5%
The Redesigned Large Standard System (3/8 inch Blasthead)	33.8 (ID no.3)	74.0 (ID no.4)
Increase of the Redesigned Large System than Baseline Technology	245%	239%
Increase of the Redesigned Large System than the Redesigned Standard System	111%	85.0%

3.4 PHASE III SUMMARY

Based on the proposed plan, Phase III have been fulfilled successfully. The main conclusions are as follow:

- Two types separators (the dual vibration separator and the dual centrifugal separator), the pre-separator designed for large, low-density particles created by cleaning the concrete wall and the centrifugal separator designed for separating the fine grits from the dust, have been designed for LTC 1072 machine. As expected, the dual centrifugal separator worked well and its separation efficiency for the G80 grits was almost double that of the old one.
- The radiological sensors and their electronic control system were tested by using the simulated radiation source in the lab. The result indicated the design of the rad sensor and its electronic control system was successful. The rad sensor can efficiently detect the level of contamination on the surfaces.
- The “liftoff” sensor system consisted of three proximity sensors and the electronic control system. It was designed to incorporate with the blasthead. Both the lab test and on-site test indicated this system can shut off the trigger successfully when the blasthead is taken from the surface, as expected.
- The control system can control the triggers and two type sensors for two blastheads simultaneously.
- The field verification testing has been performed at FIU-HCET’s site. The prototype of High Productivity Vacuum Blasting System works successfully for cleaning the different media surfaces. For the coated steel plate, the productivity rate of the standard blasthead prototype was increased by 63.6%; and for the concrete wall, the productivity rate of the standard blasthead prototype was increased by 83.5%. Compared to the standard blasthead prototype, the productivity of the large blasthead prototype was increase 111% for the coated steel plate, and 85.0% for the coated concrete wall.
- The tasks of Phase III this project have been successfully fulfilled. The productivity rate of the redesigned vacuum system has been increased more than 50% over the baseline technology. The research goal has been achieved.

CONCLUSION

Based on the proposed plan, this project have been fulfilled successfully. The main conclusions are as follow:

- The prototype verification testing has been performed at FIU-HCET's site. The prototype of High Productivity Vacuum Blasting System works successfully for cleaning the different media surfaces. The productivity rate and the economy of the redesigned system were increased more than 50% over the baseline technology.
- All tasks of this project have been successfully fulfilled. The objective of this project has been achieved, namely the productivity rate of the redesigned vacuum system has been increased more than 50% over the baseline technology.
- New materials, Tungsten Carbide, Boron Carbide, and Roctec 500, used to manufacture the liner to the rectangular blasting nozzle all test satisfactorily, but the Boron Carbide being much lighter is the preferred one.
- Two type separators, the pre-separator designed for large, low-density particles created by cleaning the concrete wall and the centrifugal separator designed for separating the fine grits from the dust, have been designed and fabricated, and their separation efficiencies have been measured. The test results show that the two type separators can work well as expected. The separation efficiency of the centrifugal separator for the G80 grits was almost double that of the old one.
- The radiological sensors and their electronic control system were tested by using the simulated radiation source in the lab. The result indicated the design of the rad sensor and its electronic control system was successful. The rad sensor can efficiently detect the level of contamination on the surfaces.
- The "liftoff" sensor system consisted of three proximity sensors and the electronic control system. It was designed to incorporate with the blasthead. Both the lab test and on-site test indicated this system can shut off the trigger successfully when the blasthead is taken from the surface, as expected.
- The control system can control the triggers and two type sensors for two blastheads simultaneously.

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APPENDIX A

AUTOCAD DRAWINGS FOR THE REDESIGNED BLASTHEAD

THE STANDARD BLASTHEAD PROTOTYPE (1/4 INCH SIZE)

The AutoCAD drawing of the standard blasthead

The AutoCAD drawing of the nozzle insert for the standard blasthead

The AutoCAD drawing of the nozzle insert housing for the standard blasthead

The AutoCAD drawing of the outside shell for the standard blasthead

The AutoCAD drawing of the inside tube for the standard blasthead

The AutoCAD drawing of the outside tube for the standard blasthead

The AutoCAD drawing of the connection component for the standard blasthead

The AutCAD drawing of the wind curtain for the standard blasthead

THE LARGE BLASTHEAD PROTOTYPE (3/8 INCH SIZE)

The AutCAD drawing of the large blasthead

The AutoCAD drawing of the rectangular nozzle insert for the large blasthead

The AutoCAD drawing of the nozzle insert housing for the large blasthead

The AutoCAD drawing of the inside tube for the large blasthead

The AutoCAD drawing of the connection component of the large blasthead

The AutoCAD drawing of the outside shell for the large blasthead

The AutoCAD drawing of the wind curtain for the large blasthead

APPENDIX B

AUTOCAD DRAWINGS FOR THE VIBRATION SEPARATOR

Technical drawing of a BIG PARTICLE WITH LOW DENSITY SEPARATION SYSTEM. The drawing includes a side view on the left and a front view on the right. The side view shows a vertical assembly with a top section of 1'-8", a middle section of 1'-3", and a bottom section of 1'-4". A horizontal section of 3'-3" is also indicated. A detail callout 'Detail 1' points to a specific component. The front view shows a vertical assembly with a top section of 2'-4" and a middle section of 3'-3". A horizontal section of 8" is also indicated. The drawing is titled 'BIG PARTICLE WITH LOW DENSITY SEPARATION SYSTEM'.

Date: August 16, 1999	
Scale: Drawing To Scale	Third Angle
HAJUN KANG	PROJECT MANAGER
DAVID GUASCA	RESEARCH ASSISTANT
Hemispheric Center for Environmental Technology Florida International University, Miami Florida 33199 Phone: (305) 348-1996	
Drawing Number	1

THE DUAL VIBRATION SEPARATOR

The AutoCAD drawing of the dual centrifugal separator (front view)

The AutoCAD drawing of the dual centrifugal separator (top view)

The AutoCAD drawing of the dual centrifugal separator (side view)

APPENDIX C

AUTOCAD DRAWINGS FOR THE CENTRIFUGAL SEPARATOR

THE SINGAL CENTRIFUGAL SEPARATOR

Date: January 26, 2000

Scale: Drawing to Scale

Third Angle

PROGRAM MANAGER

PROJECT MANAGER

RESEARCH ASSISTANT

HCET

Hemispheric Center for Environmental Technology
Florida International University

Material: Steel

Centrifugal Separator

PROJECT:

HCET-1998-M005

THE DUAL CENTRIFUGAL SEPARATOR

The AutoCAD drawing of the dual centrifugal separator

The AutoCAD drawing of the dual centrifugal separator (Side view)

The AutoCAD drawing of the dual centrifugal separator (top view)

APPENDIX D

PICTURES OF THE NEW DESIGNED COMPONENTS

THE STANDARD BLASTHEAD PROTOTYPE (1/4 INCH)

The standard blasthead

The rectangular nozzle insert and its housing for the standard blasthead

The nozzle insert housing and inside tube for the standard blasthead

The outside shell, tube and connection component for the standard blasthead

The brush ring and wind curtain for the standard blasthead

The brush ring and wind curtain for the standard blasthead

THE LARGE BLASTHEAD PROTOTYPE (3/8 INCH)

The large blasthead

The rectangular nozzle insert and its housing for the large blasthead

The inside tube for the large blasthead

The wind curtain, brush ring, sensor shelf, and connection component for the large blasthead

BLASTING SENSORS

The proximity sensor

The radiological sensor

The electronic control box

Monitoring screen

THE SINGLE VIBRATION SEPARATOR

The single vibration separator

The dust collecting box for the single vibration separator

THE SINGLE CENTRIFUGAL SEPARATOR

THE DUAL CENTRIFUGAL SEPARATOR

APPENDIX E

FIU-HCET TEAM MEMBERS

FIU-HCET TEAM MEMBERS FOR THIS PROJECT

Name	Title
Bo Zheng	Project Manager
Haijun Kang	Mechanical Engineer
Eric Shea	Mechanical Engineer
Rodrigue Ade	Electronic Engineer
Hayri Sapmaz	Mechanical Engineer
Lee Schneider	Machinist Specialist
Keith Welker	Electronic Engineer
Richard Musgrove	Electronic Engineer
Walter Conklin	Senior Mechanical Engineer
Leonel Lagos	Group Leader
Amer Awwad	Program Manager
Jinglian Xu	Mechanical Engineer
Lakshmikanth Nandanuru	Research Assistant
David Guasca	Researcher Assistant