Recovery of a Recyclable Metal Alloy From High Speed Steel Grinding Swarf
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FINAL

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ACKNOWLEDGMENTS

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?? Greenfield for supplying the metal-bearing swarf samples; and
?? Timken-Latrobe for evaluating the scrubbed sample for potential use as a feedstock.

About the Minerals Research Laboratory

The Minerals Research Laboratory (MRL) is one of 22 research divisions operated under the direction of the College of Engineering at NC State University. The MRL was established in 1946 to assist in the development of North Carolina's mineral resources through research and development. Over the years the activities of the laboratory have expanded to include R&D work for sponsors in all fifty states and throughout the world. The main focus of MRL's research is the beneficiation of industrial minerals.
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1.0 INTRODUCTION

This project evaluated the feasibility of the separation and subsequent recovery of steel from the grinding swarf resulting from the high-speed tool cutting process. Swarf is a mixture of small metal particles, cooling fluids, lubricants, and residuals from grinding media such as abrasive belts or stone wheels. Swarf is typically high in liquid content due to the amount of cooling/cutting fluids that are used in the grinding process. The mixture of liquids and fine metal particles makes the swarf a dense, and hard to manage material.

Depending on the cutting and grinding process and type of steel being cut, residual swarf usually contains steel cuttings, filter media, coolant oil, burr grit, phosphorus, and other potential contaminants. In many cases, swarf is landfilled, although the metal, oil, and filter media, if separated, are valuable feedstock materials.

The contaminants typically found in swarf cause technical problems in a remelt process. Too much oil can cause fires or explosions during remelt and introduce air quality problems. Nonmetal solids create excess slag in the remelt mandating additional, reducing metal yield and adding costly separation steps. Also, the phosphorus concentration in the metal must be extremely low, as it causes faster deterioration of the tool metal in the final product. Due to these potential problems, several large-volume metal producers in the U.S. convened and stipulated limitations on these materials in a recovered metal. Specifically, oil must be removed to be less than 3% of the mix; nonmetals must be less than about 5% of the mix, and

The primary objective of this project was to develop a scrubbing and separation technology that would produce a recyclable metal alloy acceptable as a feedstock source for smelters, tool manufacturers, or other consumers of quality steel.

A meeting was held in August 1996, facilitated by the Center for Waste Minimization, and included three major cutting tool manufacturers (CTM) and three high speed steel (HSS)
producers. This meeting achieved acceptance of the prior work done on this swarf recovery method. This group agreed on the makeup of the recovered metals and allowable contaminants that would allow use of the product in their processes. Those initial specifications were:

<table>
<thead>
<tr>
<th>Component</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Content</td>
<td>less than or equal to 5%</td>
</tr>
<tr>
<td>Nonmetallics</td>
<td>less than or equal to 14%</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>less than or equal to 0.10%</td>
</tr>
</tbody>
</table>

Subsequent to this meeting, and during the course of the scrubbing and separation trials conducted under this project, the HSS producers stipulated a more stringent set of target specifications for the recovered metal:

<table>
<thead>
<tr>
<th>Component</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Content</td>
<td>less than or equal to 3%</td>
</tr>
<tr>
<td>Nonmetallics</td>
<td>less than or equal to 5%</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>less than or equal to 0.03%</td>
</tr>
</tbody>
</table>

The 0.03% phosphorus limit is the maximum allowed by the accepted standard for all HSS grades by the HSS producers and CTMs as buyers. This specification is not negotiable.

During the scope of the project, Timken-Latrobe changed the nonmetallic limit once again, to be less than 3%. These specifications require a fairly high purity product, which requires significantly more effort than the original limits of 5% oil, 14% nonmetallics and 0.1% phosphorus.

The markets for recovered swarf are somewhat limited. Tool manufacturers typically utilize 40 to 60% recycled metal in production of new tools, however, the metal must be fairly pure as indicated by the contaminant limitations noted above. Timken-Latrobe is not the only potential buyer. However, since the aforementioned meeting, two of the major HSS producers are no longer producing HSS in quantity for CTM consumption and therefore are not viable markets. Timken-Latrobe is the only remaining HSS quantity producer in the United States (U.S.).

There are a few specialty steel producers in the U.S. that may be interested in the scrubbed swarf. Some of these producers require Molybdenum as a feedstock. Typically, 5% to 8% of
HSS swarf is molybdenum. Several years ago, one such company was purchasing dried, unwashed swarf from HSS production, for $200 per ton for use in non-HSS products; they may still be a potential buyer.

Other HSS producers exist in the foreign arena. The metal in the swarf can be brokered to several manufacturers/ producers overseas, especially in countries when there is a solid metal working industrial base (e.g., CTM customers) and specialty steel producer(s).

Under the scope of this project, bench-scale testing was conducted to optimize a process design for removal of the higher-value steel cuttings from the swarf, for reuse, in a pilot-scale separation. Parameters were optimized for scrubbing/washing, and separation of the metal from the remaining constituents by various means.

After acquisition of the swarf samples, the proposed test parameters for bench-scale testing originally included the following steps:

- Percent solids in the scrubbing/washing step.
- Surfactant screening in the scrubbing/washing step.
- Residence time in the scrubbing/washing step.
- Percent solids in the gravity separation step.
- Flowrate in the gravity separation step.
- Percent solids in the flotation step.
- Residence time in the flotation step.
- Reagent screening in the flotation step.
- Field strength in the magnetic separation step.
- Evaluation of the recovered metal by an end user.

As the project convened, the learnings in the early steps steered the testing in different directions than originally proposed. During pilot-scale work, the gravity separation and flotation steps were deemed unnecessary, therefore no final parameters or result are reported for those steps.

Additionally, pilot scale testing was expected to produce two, 55-gallon drums of clean metal cuttings for evaluation by Timken-Latrobe, a steel manufacturer that uses electric arc furnaces to produce their products. During bench-scale work, it was determined that Timken-Latrobe
would need 25 tons of metal cuttings to evaluate in their furnaces. Because the production of such a huge quantity of material was not possible under this project scope, only a five-pound sample of scrubbed metals was sent for evaluation at Timken-Latrobe’s lab.

2.0 PROCEDURES AND ANALYSES

The swarf samples acquired for this project were produced in a cutting tool manufacturer’s filtration circuit that recovers the majority of cooling oil for reuse. Presently, after oil removal, their swarf waste is sent to landfill for disposal. The swarf was a mixture of small cuttings of high-molybdenum steel, cutting/cooling oil, filter media, and grinding wheel grit. Two separate types of filtration media are used by the cutting tool manufacturer; perlite and diatomaceous earth (DE). Samples of swarf containing both types of filtration media were tested.

The scope of work actually performed included:

- Scrubbing and decanting of diatomaceous earth (DE) bearing swarf
- Analysis of products from scrubbing
- Fine-tuning of the scrubbing and decanting process to define the best parameters
- Scrubbing of perlite-bearing swarf
- Decanting after scrubbing
- Analysis of scrubbed solid cuttings for:
  - Total Petroleum Hydrocarbon (TPH)
  - Non-Metal
  - Phosphorus
- Oil recovery from decanted solutions
- Magnetic separation of scrubbed solids
- Fine tuning of the scrubbing/decanting
- Comparative testing of DE swarf using parameters established for perlite swarf
- Generation of a sample of scrubbed cuttings for evaluation by Timken-Latrobe
- Evaluation of scrubbed cuttings by Timken-Latrobe

The original scope of work suggested using gravity separation and flotation steps to aid in separation of the cuttings and the oil. However, based on the positive results during the course of the scrubbing and decanting, it was determined that these steps were unnecessary.
2.1 **Scrubbing and Decanting**

The objective of the scrubbing trials was to optimize the parameters for oil removal. The oily swarf is scrubbed sequentially with surfactant and water. The oil and surfactant intermix with the trapped water to form an emulsion, from which a portion of the oil eventually settles out.

Sequential scrubbing of the swarf with water and surfactants released a significant amount of the cutting/cooling oil from the swarf. Multiple scrubbing cycles were required to achieve adequate oil removal.

All scrubbing was performed in a six-sided stainless steel vessel that had a volume of 1200 milliliters, height of 18 centimeters, and an approximate diameter of 9 centimeters. The agitating shaft has three sets of four-bladed impellers; each set with opposing pitches. Weighed samples of swarf were put in the vessel, and the appropriate amount of water added to obtain the desired percent solids pulp density.

Surfactants were added by weight to achieve the desired surfactant strength in relation to the water weight. The vessel was put in a holding frame and agitated at 1200 rpm for a prescribed time.

2.1.1 **Scrubbing/Decanting of Diatomaceous Earth Swarf to Optimize Scrubbing Parameters**

The scrubbing trials were initiated with the DE swarf samples first. A total of 147 scrubbing tests were conducted on the DE-bearing swarf. The scrubbing tests intended to:
1) Evaluate the effect of addition rates of various surfactants and how these addition rates, which determine the surfactant strength, influenced the release of the cutting/cooling oil from the swarf; and

2) Evaluate the effect of the pulp density (in percent solids) of the scrubbing operation

Four surfactants were evaluated at varying solid densities:

?? Dow Chemical's Dowfax
?? Albright & Wilson's (A&W) CDE/A6
?? A&W BQ6
?? A&W AMT7

Each sample was scrubbed for three minutes. The resulting emulsion was decanted off, centrifuged to remove any solids, and treated with 30% sulfuric acid to break the emulsion. The acid-treated solution was put into a Babcock bottle and centrifuged overnight. The amount of oil recovered from the emulsion was measured in the neck of the Babcock bottle. The volume of oil was then translated to total oil removed, as a percentage of swarf feed weight. Oil removal data from these trials using the different surfactants are shown in Figures 1 and 2. The percent solids have definite impact on oil removal.
**Figure 1**

Effect of Percent Solids on Scrubbing
Dowfax 6-7 to 6-10

**Figure 2**

Effect of Percent Solids on Scrubbing
A&W CDE/A6
A significant observation was that the A&W surfactants could be added at a much lower rate than the Dow surfactant to achieve the same activity. A 1% addition of the A&W CDE/A6 removed more oil than a 5% addition of the Dowfax surfactant. This indicated that the A&W surfactant had a much higher activity.

The scrubbed solids were filtered, dried, and weighed to estimate how much of the nonmetallics (e.g., filter media and grinding grit) were released from the swarf. The weight reduction data for these trials is shown in Figures 4 and 5.

Photomicrographs at this stage of the trials were taken of the DE filter media, the untreated swarf, and the scrubbed swarf. The photos showed that removal of the oil and alloy was difficult to achieve evidenced by a significant amount of material in the cavities of the spherical DE media particles.

When tested, the A&W AMT 7 surfactant created an emulsion that was so stable that phase separation in the Babcock bottles could not be accomplished even after 48 hours of centrifuging; probably due to the extremely small diameter of the bottle’s neck. Such an extended time frame for phase separation would make this surfactant unsuitable for full production processing; therefore it was eliminated from the choices.

The A&W BQ6 surfactant created an emulsion that would separate in an overnight centrifuging time frame, but did not perform nearly as well as the A&W CDE/A6 surfactant in terms of oil removed from the emulsion. This surfactant was also eliminated from the choices.

A pH adjustment scenario was also tried at the suggestion of Dr. Kotvis of Benz Oil, the company that produces the cutting oil used by Greenfield Kennametal. Dr. Kotvis stated that adjusting the pH during scrubbing of the swarf may create an emulsion, thereby removing the oil. The natural pH of a swarf slurry is about 8.0 to 8.8. Several pH adjustments were evaluated,
by changing the concentration of sodium hydroxide solution, to achieve a pH of 9, 10, 11, 12, 13, and 14. The adjustments had little to no impact on oil removal.

Based on preliminary data from theses initial scrubbing tests of the DE swarf, a 30% solids pulp density was chosen as the scrubbing pulp density for evaluating the other surfactants for the DE swarf. The A&W CDE/A6 surfactant, at 1% strength, was deemed the optimal surfactant and addition rate.

The data showed that the A&W CDE/A6 was the surfactant that had performed the best, therefore it was used in all subsequent trials. The pH during scrubbing was typically 8.8. An anti-foaming reagent was necessary due to the foam created by the A&W CDE/A6 that, in some cases, made decanting of the emulsion difficult.

Multi-stage scrubs of three-minute durations were performed to evaluate the effect of time and multiple additions of surfactant. In the first cycle, surfactant was added at 1% strength. The emulsion from the first cycle was removed, and water was added to make up the volume for the cycle 2 scrub. This procedure was repeated for two more cycles without adding surfactant. At cycle 5, more surfactant was added at 0.5% strength, and the process was repeated once more for a total of eight cycles. The time allotted for the oil to settle out for these test cycles varied from six to 18 minutes. Pilot testing would be necessary to determine a constant settle time.
Figure 3 shows that with each sequential scrubbing cycle, more oil was removed, although incrementally less oil was removed with each cycle. When an additional dose of surfactant was added, a spike in oil removal was manifested. Some constituent of the oil separated out as an unidentified orange product, which was measured and included in Figure 3.

![Figure 3](image-url)

**Figure 3**

As a result of this testing, and the analysis of a few samples, for which the data is provided in Section 3.0 of this report, the parameters shown in Table 1 were established for the DE swarf scrubbing.
Table 1 – Initial Scrubbing Parameters for DE Swarf

<table>
<thead>
<tr>
<th>Definition of Parameters for Scrubbing Stage</th>
<th>Parameter (as Tested)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent solids (pulp density)</td>
<td>30%</td>
</tr>
<tr>
<td>Surfactant add rate (strength)</td>
<td>Variable, 1 and 0.5% additions</td>
</tr>
<tr>
<td>Number of scrub cycles</td>
<td>8</td>
</tr>
<tr>
<td>Residence time in each rubbing/washing cycle</td>
<td>3 Minutes</td>
</tr>
<tr>
<td>Residence time for oil settling and removal step</td>
<td>6-18 minutes</td>
</tr>
<tr>
<td>pH</td>
<td>Not tested</td>
</tr>
<tr>
<td>Foaming reagent</td>
<td>None</td>
</tr>
</tbody>
</table>

Various scrubbed DE samples were submitted for total petroleum hydrocarbon (TPH) analysis. The analysis indicates the amount of residual cutting oil remaining in the solids. Samples were chosen based on the Babcock test data which indicated relative amounts of oil removed. Figure 4 shows results from the TPH analyses on the DE samples. The best result was the product scrubbed with the A&W surfactant, at 30% solids. That sample achieved a 7.5% TPH, from a starting feed swarf that contained 14 to 15% TPH.

Figure 4
2.1.2 Scrubbing and Decanting of Perlite Swarf to Optimize Scrubbing Parameters

Initially the scrubbing trials on the perlite swarf were conducted using the same parameters as those established for the DE swarf; at 30% solids pulp density, and 1% A&W CDE/A6. A total of 145 scrubbing test stages were conducted on the perlite swarf. These tests evaluated high pulp density scrubbing and various scenarios of decanting to remove the nonmetallics.

After an initial set of trials, it became apparent that the oil removal was not approaching desired levels, and changes were required in the scrubbing parameters. The A&W CDE/A6 surfactant was still used in all trials, but addition rates varied, up to as high as 2.6% by weight in the water used in the scrub. The solids pulp density was increased to 60%. The high solids content helped to generate heat during the scrubbing process, and seemed to facilitate release of the cutting oil.

Multi-stage scrubs of 6 to 11 stages were run. Scrubbing times used were 60 minutes per perlite removal stage and 10 minutes per oil removal stage. After the scrubbing time for a given stage would elapse, the slurry was allowed to settle for approximately 10 minutes. Decanting was performed, and the solids remaining in the scrub vessel were subjected to another stage of scrubbing.

To remove the perlite from the scrubbed material, water was poured into the scrubbing vessel, and the solution was allowed to overflow from the vessel. During the oil removal stages, water was poured into the scrubbing vessel, and the solution was poured from the vessel.

The variable effects of time and different solid densities on the scrubbing of the perlite samples, as done with the DE samples, was not evaluated. This would be essential research for any pilot scrubbing.

Per a photomicrograph comparison to the DE filter media, the perlite appeared to clean more efficiently. This is perceived to be due to difference in surface structure of the perlite compared
to the DE swarf. The perlite has more of a laminar, platelet configuration and fewer cavities than the DE.

All of the fully scrubbed samples, six in total, were submitted for TPH analysis, with the results compiled in Figure 5 below. Note that the y-axis is a logarithmic scale, and that the differences in TPH between the swarf and the scrubbed samples is significant.

Per the TPH analysis, a 98% or better removal efficiency of the cutting oils was achieved on all the samples. This level is within the criteria for oil removal established by Timken-Latrobe.

![Figure 5: Compilation of Total Petroleum Hydrocarbon Analysis](image)

The optimized parameters determined for scrubbing of the perlite swarf are shown in Table 2. The pH of the swarf was measured at 8.8, but is not necessarily a required parameter for this scrubbing method.

**Table 2 – Scrubbing Parameters for Perlite Swarf**
<table>
<thead>
<tr>
<th>Definition of Parameter for Scrubbing Stage</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent solids (pulp density)</td>
<td>60%</td>
</tr>
<tr>
<td>Surfactant add rate (strength)</td>
<td>2%</td>
</tr>
<tr>
<td>Number of scrub cycles</td>
<td>11</td>
</tr>
<tr>
<td>Residence time in each rubbing/washing cycle</td>
<td>60 Minutes</td>
</tr>
<tr>
<td>Residence time for oil settling and removal step</td>
<td>10 Minutes</td>
</tr>
<tr>
<td>pH</td>
<td>8.8</td>
</tr>
<tr>
<td>Foaming reagent</td>
<td>Dow P2000</td>
</tr>
</tbody>
</table>

2.2 Oil Removal from DE Swarf Using Scrubbing Parameters Optimized for Perlite

New samples of the DE swarf were subjected to the same multi-stage scrubbing/decanting technique as that developed for the perlite swarf.

Figure 6 compares the total oil present in the feed and the resultant scrubbed solids (SS). Under these scrubbing conditions, the perlite swarf appears to be more readily cleaned, likely due to its laminar nature and absence of any voids. The photomicrograph also indicated better oil removal, with oil more visible in the cavity-laden surface of the DE swarf.
2.3 Metal Separation Trials on Scrubbed Solids

According to Timken-Latrobe, any primary furnace feed with a nonmetal content of over 3% creates excess slag in the melt. This excess slag requires extra heating reagents (shredded aluminum and ferro-silicon) in the refining furnace, which affects the economics of the process. Timken-Latrobe originally stated that a nonmetallic content of less than 6% by weight would be acceptable for reuse in their process. Later in the scope of this project, they revised this limit to a metals content of no greater than 3 %, and preferably 2% by weight. Figure 7 shows the nonmetal content of the perlite feed and resulting scrubbed samples, prior to any metal separation. Achieving a nonmetal content of less than 3 % is not possible without magnetic or other separation techniques.
2.3.1 Separation by Gravity Concentration

Four scrubbed samples from the initial DE swarf scrubbing were subjected to gravity concentration in a Krebs Uniclone cyclone. Underflow and overflow samples were put in a lab oven for drying, but the oven was inadvertently set at a temperature so high that the samples charred and were ruined. At the same point in time, the sump for the cyclone developed a major leak. By the time a new sump was fabricated and installed, testing on the perlite swarf showed that scrubbing and decanting were inadequate for a metal-nonmetal separation.

Therefore, no more gravity concentration work was pursued. In addition, the specific gravity difference between the filter media, for both the DE and the perlite, as well as the grinding grit, is minimal, making it impractical to separate and subsequently recycle the filter media using this method.
2.3.2 Magnetic Separation

Two methods of magnetic separation were conducted to determine the best means of removing the recyclable magnetic metal portion from the scrubbed solids recovered from the perlite-bearing swarf.

The first method conducted was the “Davis Magnetic Tube Testing” method. Two scrubbed samples recovered from the perlite-bearing swarf were submitted to Michigan Technological University. The separation test was conducted on samples from 10/18/99 and 10/28/99.

The separation trials were conducted under the following test conditions:

Water flowrate: 380 ml/min  
Reciprocation rate: 85 strokes/min  
Magnet current: 2 amps  
Time: 10 minutes  
Drying temperature: 105 degrees Celsius

The scrubbed samples from 10/18/99 resulted in 80.78% magnetics and the scrubbed samples from 10/28/99 resulted in 75.52% magnetics. The non-magnetic portion of the solids still contained a significant amount of metal, unacceptable for use by Timken-Latrobe.

Using this separation technology, the non-metal content is greater than acceptable for the potential end user of the recovered cuttings.

A second method of magnetic separation, called wet high intensity magnetic separation (WHIMS) was conducted on by International Process Systems. The best sample achieved to date, from the perlite-bearing swarf, scrubbed on from 01/14/00, was submitted.

The WHIMS technology involves mixing the sample in a slurry, then passing it through a vertical wheel which incorporates a field perpendicular to both the plane of the wheel and the slurry
flow. The flow is passed through the wheel twice in opposite flow directions. Various alterations on the wheel matrix are available for different applications.

This test was only preliminary and feed rate and machine settings were not optimized. Using this technology of separation, and testing the final product for magnetic content after the final pass of the slurry through the wheel matrix, a total of 94.86% of the feed was reported to be magnetic product. On the first pass, 78.83% of the magnetics responded very strongly to the magnet, even using a low field strength.

These preliminary results indicate that the WHIMS magnetic separation process can reduce the nonmetallics to about 3.09 percent of the feed weight, possibly less with optimization of the process. This level of nonmetallics would be acceptable for use by Timken-Latrobe.

If the WHIMS technology were used in full production, initial separation could easily achieve about 75% removal of the magnetics with a low-intensity wet drum separator. The final pass could then be through the WHIMS matrix to remove the remaining magnetics.

### 2.4 Phosphorus Analysis of Scrubbed Samples

Phosphorus elimination was not complete in the scrubbing process used. Elimination is difficult, hypothetically because the phosphorus contained in the cutting oil is burned into the metal during the cutting of the drill bits.

Four scrubbed samples generated from the perlite-bearing swarf were submitted to Timken-Latrobe’s laboratory for phosphorus analysis. These were the only viable samples available at the time of the analysis.

Figure 8 shows the phosphorus content of the scrubbed solids and the perlite swarf feed.
The average phosphorus content (of scrubbed solids tested) of 0.031% compares to a typical initial content of 0.039%.

**Figure 8**

![Phosphorus Content Graph](image)

<table>
<thead>
<tr>
<th>Description</th>
<th>Phosphorus Content (% of Feed Weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perlite Swarf</td>
<td>0.039</td>
</tr>
<tr>
<td>10/04 Scrubbed Solids</td>
<td>0.028</td>
</tr>
<tr>
<td>10/28 Scrubbed Solids</td>
<td>0.031</td>
</tr>
<tr>
<td>11/18 Scrubbed Solids</td>
<td>0.035</td>
</tr>
</tbody>
</table>

### 2.5 Minimization of Scrubbing Cycles for Potential Water Conservation

In an attempt to reduce water consumption that would be required by this process if conducted on a full production bases, fewer scrubbing cycles were attempted.

Tests were conducted on two scrubbed samples (from the perlite-bearing swarf), using only six cycles in total compared to the 11 cycles used previously. Figure 9 shows the results. This testing indicates that more than six scrub cycles are needed to adequately clean the swarf. As such, this amount of water consumption, on a full-scale production basis, would be infeasible without a water recycling system.
2.6 Oil Recovery

Samples of oil, collected as free standing oil, remaining from the scrubbing tests cycles of 01/12 through 01/14 were centrifuged. The depth of the resulting layers of clean oil were measured to obtain volumetric data. The total oil recovered was calculated to be 18.2% out of the original 23.9%; or about 76% recovery. Oil remaining in suspension as an emulsion accounted for the balance of oil at a level of about 5%. Recovery of the oil in emulsion would require a sulfuric acid treatment.
3.0 CONCLUSIONS

Results of these pilot scrubbing trials lead to a number of conclusions and recommendations for additional research. One major finding is that the perlite-bearing swarf cleaned better than the DE-bearing swarf using this scrubbing technology.

A brief evaluation of this swarf recovery method, by the Center for Waste Minimization of South Carolina (CWM), was positive. Staff at the CWM have significant experience in swarf recovery research. The CWM feels that the process is fairly simple and straightforward and achieves good results. The value of the metal and the residual oil for use as a fuel remains high.

The labor required to operate 11 scrubbing cycles would be minimized in a production mode, by utilizing a cascading scrubber where one scrubber discharges into the next. When upstream scrubbed material is introduced to the next sequential scrubber, the scrubbed material would be forced out from that unit to the next. This is envisioned to be a complex plumbing system as the wet swarf is very fluid. Additionally, if a water reclamation system were developed, the water consumption for the sequential scrubbing would be minimized.

The optimal parameters for scrubbing the swarf feed using this process are:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent solids (pulp density)</td>
<td>60%</td>
</tr>
<tr>
<td>Surfactant</td>
<td>A&amp;W CDE/A6</td>
</tr>
<tr>
<td>Surfactant add rate (strength)</td>
<td>2 – 4 %</td>
</tr>
<tr>
<td>Number of scrub cycles</td>
<td>11</td>
</tr>
<tr>
<td>Residence time in each rubbing/washing cycle</td>
<td>60 Minutes</td>
</tr>
<tr>
<td>Residence time for oil settling and removal step</td>
<td>10 Minutes</td>
</tr>
<tr>
<td>Foaming reagent added</td>
<td>DOW P2000</td>
</tr>
</tbody>
</table>

Additional findings are presented below.
3.1 Evaluation of Scrubbed Sample for Use by Potential End User

Timken-Latrobe is one of the potential end user for the scrubbed metals. They stipulated the final criteria\(^1\) for oil, nonmetals and phosphorus, to render the metal usable in their process. Other end users may have less stringent criteria, however, they have not been approached under this research project. Timken-Latrobe’s criteria is as follows:

<table>
<thead>
<tr>
<th>Residual Oil Content:</th>
<th>Less than or equal to 3%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorus Content:</td>
<td>Less than or equal to 0.03%</td>
</tr>
<tr>
<td>Nonmetallics Content</td>
<td>Less than or equal to 3%</td>
</tr>
</tbody>
</table>

During bench-scale work, it was determined that Latrobe would need 25 tons of metal cuttings to evaluate in their furnaces. The production of such a huge quantity of material was not possible under this project scope, only a five-pound sample of scrubbed metals, from the perlite-bearing swarf was submitted to Timken-Latrobe for evaluation as a suitable feed for remelt. This sample had not undergone any metal separation technique, such as WHIMS.

Their analytical results showed that the sample had 8.6\% nonmetallics by weight, which is too high for their remelt due to generation of excess slag in the melt. A lab-scale melt test would not mimic the same chemical or metallurgical conditions as those in the 25-ton production furnaces. They would require Therefore Latrobe did not perform further testing. The feedback from Latrobe was not particularly useful.

Other potential end uses for the scrubbed metals exist, but were not contacted in the scope of this project. It is likely that other end users, especially foreign markets, would purchase the scrubbed solids at the level of purity that this technology is capable of producing.

\(^1\) Initial criteria stipulated, per the Introduction section of this report:

<table>
<thead>
<tr>
<th></th>
<th>less than or equal to 5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Content</td>
<td></td>
</tr>
<tr>
<td>Nonmetals</td>
<td>less than or equal to 14%</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>less than or equal to 0.10%</td>
</tr>
</tbody>
</table>
3.1.2 Phosphorus Removal

Phosphorus content of the samples analyzed indicate that the level, at an average of 0.031%, is still too high for use by Timken-Latrobe. This level must be below the maximum allowable phosphorus limit of 0.03%, which is the accepted standard for all HSS grades. This specification is not negotiable in the U.S. Since the amount of phosphorus present in the scrubbed solids is close to this limit, there may be simple methods of achieving less than 0.03% phosphorus content.

3.1.3 Magnetic Separation

The first magnetic separation technology, the Davis Magnetic Tube Testing method, yielded inadequate metal removal. The WHIMS technology significantly reduced the nonmetallics in the scrubbed solids, to 3.09%. This removal level could likely be improved with optimization of the WHIMS process. The WHIMS or another technology that produces less than about 3% nonmetallics in the scrubbed solids is necessary to produce a feed acceptable for remelt.

Capital investment in the WHIMS technology would cost approximately $20,000. Labor and power costs are unknown. Therefore, it remains uncertain whether the WHIMS system would be a cost-effective means of metal removal.

3.1.3 Oil Removal

The scrubbing and decanting sequence, through 11 cycles, provides adequate oil removal for use of the scrubbed solids in Timken-Latrobe’s processes. 76% of the contained oil was easily removed during scrubbing and decanting, and appears clean enough for alternative uses, such as cogeneration. However, the oil was not tested for this or any other end use.
3.2 Recovery of Other Constituents from the Swarf

3.2.1 Oil Recovery

The bulk of the oil used by CTMs is a light Arabian crude oil that is refined for the cutting tool grinding application. It is not a complex synthetic oil, therefore, it separates fairly easily. The oil is unique, however, as it has a special organic phosphorous ester additive.

The recovery of oil from the oily swarf is important as it can be sold and used as fuel. This scrubbing method achieved a significant recovery rate at about 76% and the recovered oil appears clean enough for fuel, possibly cogeneration fuel. However, the oil was not tested for this or any other end use. Additional oil could be extracted from the emulsion that remains after scrubbing, through sulfuric acid treatment of the emulsion. Cost-effectiveness of this was not addressed in the scope of this project.

3.2.2 Filter Media Recovery

The lack of a significant difference in specific gravity between the filter media and the grinding grit, for both the DE and the perlite-bearing swarfs, made it impractical to separate and subsequently recycle the filter media. This would likely be impractical in full-scale production as well.

3.3 Additional Recommended Research

Additional research is recommended for further optimization of this process for full-scale production, as well as several other recovery opportunities. Potentially, the majority of the cutting/cooling oil could be recovered for use as a co-generation fuel source or other beneficial end use. Removal of the oil may also reduce the amount of the phosphorus-bearing constituent that affects the quality of the remelt.
Minimizing water consumption in the scrubbing cycles by implementing a water reclamation system would be beneficial. This could allow reuse of the reclaimed water back into the scrubbing process.

The flowsheet shown in Figure 10 was developed based on this experimentation, assuming oil recovery and water reclamation is possible. This flowsheet model could be used for as a starting point for an extended pilot-scale research project.

**Figure 9**
4.0 OTHER RESEARCH PROJECTS IN SWARF RECOVERY

Additional work related to swarf recovery has been and is being conducted by the following companies. This is not an all-inclusive listing.

?? Summary of Research and Literature Review in Preparation for this Project

United Greenfield Division of TRW, Inc.,
The R&D department attempted to process swarf by heating to drive or burn off the oils. The process failed because the swarf oxidized and doubled in volume. In addition, spontaneous combustion during hot weather was a potential hazard.

University of South Carolina
In a 1995 study, funded by the US Department of Energy, the 40-hour study proved that oil could be removed from swarf through a washing process. The study was very cursory and did not optimize the washing process.

University of South Carolina
A Chemical Engineering professor evaluated liquid carbon dioxide to clean the swarf. Analysis of the resulting samples showed that the phosphorus and nonmetallics remained, which would require secondary operations for removal. The approach appeared to be investment cost-prohibitive and somewhat complex.

A 1997 bench-scale lab was funded by the United States Cutting Tool Institute, with good success in contaminant removal, however no further details are known.

?? International Metals Reclamation Company, Inc. (INMETCO)
Ellwood City, PA

INMETCO directly recovers approximately 59,000 tons of materials annually that would otherwise be disposed of in landfills and returns these materials as products and co-products to the commercial mainstream. Metals recycled from batteries is included with a wide range of
nickel, chromium, and iron bearing wastes from stainless steel manufacturing known as millscale, 
swarf, and flue dust. In 1995, they produced over 24,000 tons of stainless steel remelt alloy, 
which was sold back to industry.

Any waste stream containing nickel, chromium, iron, molybdenum, cadmium and/or iron could 
be considered acceptable since each waste stream is evaluated on a case-by-case basis. 
Reference:  http://www.inmetco.com/

An article on INMETCO's metal recycling activities is located at:
http://www.dep.state.pa.us/dep/rachel_carson/profiles/awards/1995/inmetco.htm

?? Phoenix Environmental, LTD. (PEL)

This consulting firm, has contracted with Timken Co., Canton, Ohio, to construct a facility that 
uses metal-bearing materials as feedstock in the manufacture of magnetite products. The 
ingredients include dust, metal grindings, and scale. Magnetite is sold as a raw material to 
manufacturers of blasting media, shingle granules, pigments and colorants for paint and concrete, 
and filler additives for plastic. For more information, contact:

Phoenix Environmental Ltd
Montgomery, PA
Phone: (570) 547-2412
Olympic Manufacturing Environmental, LTD. (PEL)

Metalworking Coolant Recycling at Olympic Manufacturing

By installing a recycling system for the coolant used in their metalworking (roll threading machines), Olympic Manufacturing was able to reduce coolant disposal by 75% and solid waste disposal by approximately 88%.

Reference: http://www.magnet.state.ma.us/ota/cases/Olympic.htm

SUNYAB Center for Integrated Waste Management

With the support of the Empire State Development’s Environmental Management Investment Group (EMIG), the SUNYAB Center for Integrated Waste Management completed a Targeted Industrial Waste Inventory (TIWI) in 1998. The purpose of the TIWI project was to develop an information base on the industrial non-hazardous solid waste disposal/recycling characteristics of key industrial sectors in the Western and Finger Lakes regions of New York State.

The TIWI project revealed certain common industrial waste streams that offer opportunities for reduction and recycling. This project focused on one such industrial waste stream - metal grinding swarf. In the TIWI sample of small and mid-size companies, four industries produced an average of 200 ton/year of swarf with an average management cost of over $100 per ton.

As follow-up to TIWI, this RD&D project was undertaken to assist industries that undertake metal fabrication/preparation processes, reduce the amount of grinding swarf being sent to landfill. The project approach was designed to create greater recycling/reuse opportunities for grinding swarf through: identifying potential categories of end-uses for the material; identifying specific end-users within those categories; identifying end-user’s material specifications; thoroughly characterizing swarf produced by two participating industries; and carrying out economic and technology analyses which will help industries proceed with swarf recycling. The
benefits to the two individual companies participating in the project, and eventually to other New York State industries, are to lower their waste disposal and management costs; reduce their liability concerns related to land disposal; and to allow for greater production capacity leading to job retention and creation.

The two companies that participated in the project were two of the largest producers of grinding swarf identified during the TIWI project. The companies are well-established manufacturers of metal goods and both have considerable market share in their respective product fields. Both companies have a demonstrated commitment to waste reduction activities and are former recipients of the NYS Governor’s Pollution Prevention Awards. In order to maintain company confidentiality the companies are referred to in this report as Company One and Company Two.

Results
The project was successful in accomplishing the following:

- conceptualization of several end uses for the swarf material;
- identification of particular companies within those end-use categories;
- identification of end-user requirements for the material which would make it most useful to them;
- determination of physical and chemical characterization of several swarf samples from the two participating companies based on the parameters identified by the potential end users;
- linking one of the participating companies with potential end-users who expressed an interest in the material;
- identification of technologies to prepare the material in a way that maximizes its value to end-users.

In addition:

- Company One has recently purchased a coolant recovery technology, which will save the company over $70,000 per year in avoided transportation and disposal costs, as well as in purchased coolant savings, The company is currently working with a metal powder supplier on ways to re-use grinding swarf material. The end-user was identified by the UB team during the course of the project. If the product proves to be acceptable the generator of the swarf and the metal powder supplier will benefit substantially.
Based on Company Two’s increased awareness of the value of the swarf, they were able to find a recycling outlet that reduced their costs an estimated $15,000 per year. During the course of the project, Company Two was able to renegotiate terms with one its waste management contractors. The contractor agreed to recycle the swarf with the company’s other metal by-products, instead of disposing it as a special industrial waste.

CONTACT:
Louis P. Zicari, Jr.
Center for Integrated Waste Management
Buffalo, New York 14260-4400
e-mail: int_wastes@acsu.buffalo.edu

Hyde Manufacturing, Massachusetts

Hyde is a manufacturer of high-quality, high-carbon blades and handtools. Hyde does not use any filtration media in their grinding process. The resulting swarf product is about 70% metal and about 28% debris from the grinding bits, which typically includes some aluminum oxide and ceramic. The metal portion contains a number of different metals, including nickel. Therefore to use as remelt in a smelter or foundry, the mixture requires some heat treatment, which makes the material a less desirable feedstock to a foundry. The swarf mixture has a clean Toxicity Characteristic Leaching Procedure (TCLP) and thus is legal to landfill.

For the past four years, Hyde has recycled its swarf by giving it to a company who makes a paving material from 15% swarf. Another feedstock for the paving product is petroleum-contaminated soil. Recently (2000), the landfill has reduced the disposal tipping fee for the contaminated soil from $80/ton to $20/ton. Therefore, due to economics, the paving manufacturing company will no longer be buying the soil or the swarf as feedstocks.

Hyde has attempted to make and test out other products utilizing their swarf. Two of the products are bricks, and jersey barriers. They have not pursued marketing of such products due to potential state regulations in surrounding states (markets) for inclusion of metals in certain products.
Phillip Environmental

A manufacturer of automotive parts here in Michigan ships their waste grinding swarf to Phillip Environmental in Canada for metals recovery in place of landfiling. The recovered metals are blended into other materials and sold to the iron industry. The company's EMS/Pollution prevention objective/target is 100% grinding swarf recycled.
Reference: Energy and Environment Center Phone 734-769-4062

State of Illinois and Solvent Systems

The State of Illinois EPA is working with a firm (Solvent Systems) that is currently developing a method to recycle swarf from steel cutting operations. Their goal is to "bind" the swarf, in a cold process, so that the bound material melts rather than combusts when re-introduced to the smelter furnaces. Solvent Systems has received some research from the DOE Argonne National Lab to develop a binder and mixing process to form swarf briquettes. Solvent Systems has some sample briquettes which have been given a value which appears to make the process economically viable. The research has been expanded to include foundry sand and fly ash.

Contact: epa8616@epa.state.il.us

Inland Steel Company, Indiana

In 1991, Inland Steel Company, an integrated steel manufacturing facility in Indiana, conducted research under a supplemental environmental project (SEP). Their processes generate a scrubber sludge, containing waste iron oxides, as well as three metals listed in EPA’s Toxic Release Inventory: chromium, lead, and zinc.
In 1994, Inland began researching and implementing a sludge recovery plan. In an attempt to make the sludge into a useful product, they first dewatered the sludge, then tried several different formulations to create briquettes from the waste oxides for use in their furnaces. The proposed advantages to briquetting is ease of handling and the ability to impart physical properties that would enable use in the furnaces. Implementation issues arose in both the dewatering and briquetting process.

In development of the dewatering process, centrifuge performance was a problem. Also, dewatering was completed much faster than the briquettes could be manufactured, so a manufacturing line balancing problem arose.

In development of the briquetting process, several different binders and formulations were attempted. The type and amount of binders used in the briquetting is critical to the usability of the product in the furnace. The first binders utilized were molasses and whey, however these resulted in elevated concentrations of ammonia and phenol in the scrubber water blowdown. Corn syrup was also tested as a binder, which reduced the ammonia levels, but still produced some phenols. Molasses works much better as a binder for several reasons, and Inland ended up agglomerating the waste oxides with molasses and installed filters to reduce the phenol and ammonia. Other binders were tested as well, including inorganics.

Another problem with use of the briquettes in the blast furnaces was an increase in the zinc concentrations, which caused refractory lining failure. Allowable limits on zinc buildup were established. Eventually, they implemented a process that allowed significant recovery of the scrubber sludge for reuse in their furnaces, and in 1994 recycled at least 60,000 tons of iron. This corresponded to an iron ore use reduction of 35,000 tons.

It is unknown whether Inland is still recovering the waste oxides at this date and time.