CERP
Casting Emission Reduction Program

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Core Manufacturing Process Variables Study
Part I - Mixing

Test #1409-131-EU

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EPA United States Environmental Protection Agency

CISA

AFS
AMERICAN FOUNDRY SOCIETY, INC.

Armament Research, Development & Engineering Center
Picatinny Arsenal

USCAR
UNITED STATES COUNCIL FOR AUTOMOTIVE RESEARCH
DaimlerChrysler Ford Motor Company GM General Motors

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Core Manufacturing Process Variables Study
Part I - Mixing

1409-131 EU

This report has been reviewed for completeness and accuracy and approved for release by the following:

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The data contained in this report were developed to assess the relative emissions profile as the process parameters were varied using the equipment installed at Technikon. You may not obtain the same results in your facility. Data was not collected to assess casting quality, cost, or producibility.

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Executive Summary

The objective of this testing was to determine the emission levels from the core sand mixing process for the CERP standard phenolic urethane (PU) binder system. The emission data was collected according to US EPA Method 25A, Total Gaseous Organic Carbon (TGOC). Process variables (binder content, sand and ambient air temperature, sand type, mixer load and ventilation, mixing time and speed) were evaluated regarding their influence on the air borne emissions. Testing was done in two blade type mixers: a low-speed Carver and a variable high-speed Simpson.

The major emissions from the PU binders were caused by the evaporation of the solvents from the liquid resin. The mixing process includes all three physical parameters influencing evaporation: temperature, effective exposed surface area, and air movement over the surface of the coated sand grains.

The primary direct emission driver was demonstrated to be sand temperature. Secondary drivers were identified to be all of the above mentioned measured parameters because of their influence on the sand temperature, the amount of apparent exposed surface, and the air movement over the sand surface.

Sand temperature was constantly increased by mechanical friction. Increased mixer loading, cycle time, and higher mixing speeds caused more frictional heating. The ambient air temperature and the mixer ventilation rate each affected the sand temperature buy influencing how the sand gets rid of its heat. The mixer speed and loading additionally altered emissions, because, the speed causes the mixer tools (plows or blades) to distort the at-rest shape of the sand creating more apparent surface and exposing the sand to more relative air movement. Emissions increase with binder content but not in proportion because the binder coating only increases in thickness without creating more new surface. Finally, the sand particle sizing influenced the emissions because of its corresponding particle surface area.

The table below illustrates the relative emission concentrations measured resulting from variation of sand temperature, agitation speed, and binder content. The sand temperature range represents the start and end sand temperatures when it changed significantly during the cycle.

Type of Mixer	**% Binder (BOS)**	**Emissions in PPMV 73- 80^{o}F Sand 76^{o}F Ave. Sand Temp**	**Emissions in PPMV 71- 127^{o}F Sand 99 F Ave. Sand Temp**
7 min. cycle at 25 RPM	1.4	2068	3367
2 Min cycle at 280 RPM	1.0	1859	No data
2 min cycle at 1700 RPM	1.0	No data	4535

It must be noted that the reference and product testing performed is not suitable for use as emission factors or for purposes other than evaluating the relative emission reductions associated with the use of alternative materials, equipment, or processes. The emissions measurements are unique to the specific castings produced, materials used, and testing methodology associated with these tests, and should not be used as the basis for estimating emissions from actual commercial foundry applications.

1.0 Introduction

1.1 Background

Technikon LLC is a privately held contract research organization located in McClellan, California, a suburb of Sacramento. Technikon offers emissions research services to industrial and government clients specializing in the metal casting and mobile emissions areas. Technikon operates the Casting Emission Reduction Program (CERP). CERP is a cooperative initiative between the Department of Defense (US Army) and the United States Council for Automotive Research (US CAR). Its purpose is to evaluate alternative casting materials and processes that are designed to reduce air emissions and/or produce more efficient casting processes. Other technical partners directly supporting the project include: the American Foundry Society (AFS); the Casting Industry Suppliers Association (CISA); the US Environmental Protection Agency (US EPA); and the California Air Resources Board (CARB).

1.2 CERP Objectives

The primary objective of CERP is to evaluate the impact of new materials, equipment, and processes on airborne emissions from the production of metal castings. To accomplish this objective, the Technikon facility has been created to evaluate alternate materials and production processes designed to achieve significant airborne emission reductions, especially for organic Hazardous Air Pollutants (HAPs). HAP emissions reduction from the alternative materials, equipment and production processes is expressed as a comparison to similar emissions from a baseline or reference test. The facility has two principal testing arenas: a Pre-Production Foundry designed to measure airborne emissions from individually poured molds, and a Production Foundry designed to measure air emissions in a continuous, full-scale production process. Each of these testing arenas has been specifically designed to facilitate the collection and evaluation of airborne emissions, and associated process data. Candidate materials and/or processes are screened for emission reductions in the Pre-production Foundry and then further evaluated in the Production Foundry. The data collected during the various testing projects are evaluated to determine the impact of the alternate materials and/or processes on airborne emissions as well as on the quality and economics of casting and core manufacture. These alternate materials, equipment, and processes may need to be further adapted and defined so that they will integrate into current commercial green sand casting facilities smoothly and with minimal capital expenditure.

Pre-production testing is conducted in order to evaluate the impact on air emissions from a proposed alternative material, equipment or process. The Pre-Production Foundry is a simple, general-purpose manual foundry, which was adapted and instrumented to allow the collection of detailed emission measurements, using methods based on US EPA air testing protocols. Measurements are taken during pouring, casting cooling, and shakeout processes performed on discrete mold and core packages under tightly controlled conditions not feasible in a commercial foundry. The Pre-production foundry uses an eight-on, bottom-feed AFS step block as its test mold pattern. A report entitled Baseline Testing Emission Results – Pre-Production Foundry provides details of the baseline testing done in the Pre-Production Foundry. This report can be obtained from the Technikon web site at www.technikonllc.com.

Alternative materials, equipment and processes that, during their testing in the Pre-Production Foundry, demonstrate significant air emission reduction potential and preserve casting quality parameters are further evaluated in the Production Foundry. The Production Foundry's design as a basic green sand foundry was deliberately chosen so that whatever is tested in this facility could be easily converted for use in existing mechanized commercial foundries. The Production Foundry emulates an automotive foundry in the type and size of equipment, materials, and processes used. A single cavity automotive I-4 engine block mold is used to further evaluate materials, equipment, and processes in a <u>continuous</u> real-world production-like environment. The Production Foundry provides simultaneous, detailed, individual emission measurements, according to methods based on US EPA air testing protocols, of the melting, pouring, sand preparation, mold making, and core making processes. The Production Foundry is instrumented so that process data on all activities of the metal casting process can be simultaneously and continuously collected in order to complete an economic impact evaluation of the prospective emission reducing strategy. Castings are randomly selected to evaluate the impact of the alternate material, equipment, or process on the quality of the casting.

Test results for a particular process or product may not be the same from both foundries due to differences in the testing process. The Pre-production Foundry is designed to screen new products, processes, or equipment, whereas the Production Foundry is designed to test the effect of the product, process, or equipment in a continuous production-like environment.

The results of the testing conducted at both the Production and Pre-production Foundries are not suitable for use as general emission factors. The specific materials used (gray iron from an electric melt furnace, greensand with seacoal, and a cold box core with a relatively old resin binding system); the specific castings produced (an eight-on step block in the Pre-production Foundry and an I-4 automotive block in the Production Foundry); the specific production processes employed (a stationary hand-poured mold in the Pre-production Foundry and an impact mold line in the Production Foundry); and the specific testing conditions (relatively low stack velocity, long sampling times, high capture rates, and combined emissions from pouring, cooling and shakeout processes at the Production Foundry) produce emission results unique to the materials, castings, casting processes and measurement conditions used. The data produced are intended to demonstrate the <u>relative</u> emission reductions from the use of alternative materials, equipment and processes, and not the absolute emission levels that would be experienced in commercial foundries. A number of process parameters such as casting surface area, sand to metal ratios, pouring temperatures, stack flow rates, LOI levels, seacoal and resin contents, and the type of foundry (Cope & Drag versus Disa for example) can have a significant impact on actual emission levels.

The Production Foundry provides simultaneous detailed individual emission measurements using methods based on US EPA protocols for the melting, pouring, sand preparation, mold making, and core making processes. The core making area of the Production foundry contains three core blowers, a Georg Fischer for the preparation of automotive block cores, a Redford that is used for the production of step cores, and a second smaller Redford to produce dogbone tensile test specimens.

1.3 Report Organization

This report has been designed to document the methodology and results of a specific test plan that was used to evaluate the variability of emissions from the core mixing, making and storage process. A separate report will be issued to document the same information from the Core Making and Storage processes. Section 2 of this report includes a summary of the methodologies used for data collection and analysis, emission calculations, QA/QC procedures, and data management and reduction methods. Detailed data is included in Appendix B of this report. Section 3 of this report contains a discussion of the results.

The raw data for this test series are included in a data binder that is maintained at the Technikon facility.

1.4 Specific Test Plan and Objectives

This Part I report contains the results of testing performed to provide data on selected emissions from the core sand mixing processes. Core making and core storage results will be reported in Parts II and III of this study. The table below provides a summary of the test plan for Test EU. The details of the approved test plan are included in Appendix A.

Test Plan Summary

	Test EU
Type of Process Tested	Core Sand: Part I - Mixing Part II - Core Making (Blowing) Part III - Core Storage
Test Plan Number	1409 – 131
Binder System	Phenolic Urethane Cold Box Ashland Isocure® 905/304
Number of Tests	13 at Core Mixing (Part I); 51 at Core Making (Part II); 51 at Core Storage (Part III)
Test Dates	11/13/02 through 1/22/03
Emissions Measured	TGOC as Propane (Part I), HC as Hexane (Parts II & III)
Process Parameters Measured	Process Sand Weight; Sand and Ambient Air Temperature; Binder Concentration; Mixer Cycle Time, Loading, Speed, & Ventilation; Core Blower Cycle Time and Blow & Purge Air Pressure, Air Temperature, & Duration.
Source Parameters Measured	Mixer, Core Blower Enclosure, & Storage Enclosure Exhaust Duct Temperature, Pressure and Volumetric Flow Rate

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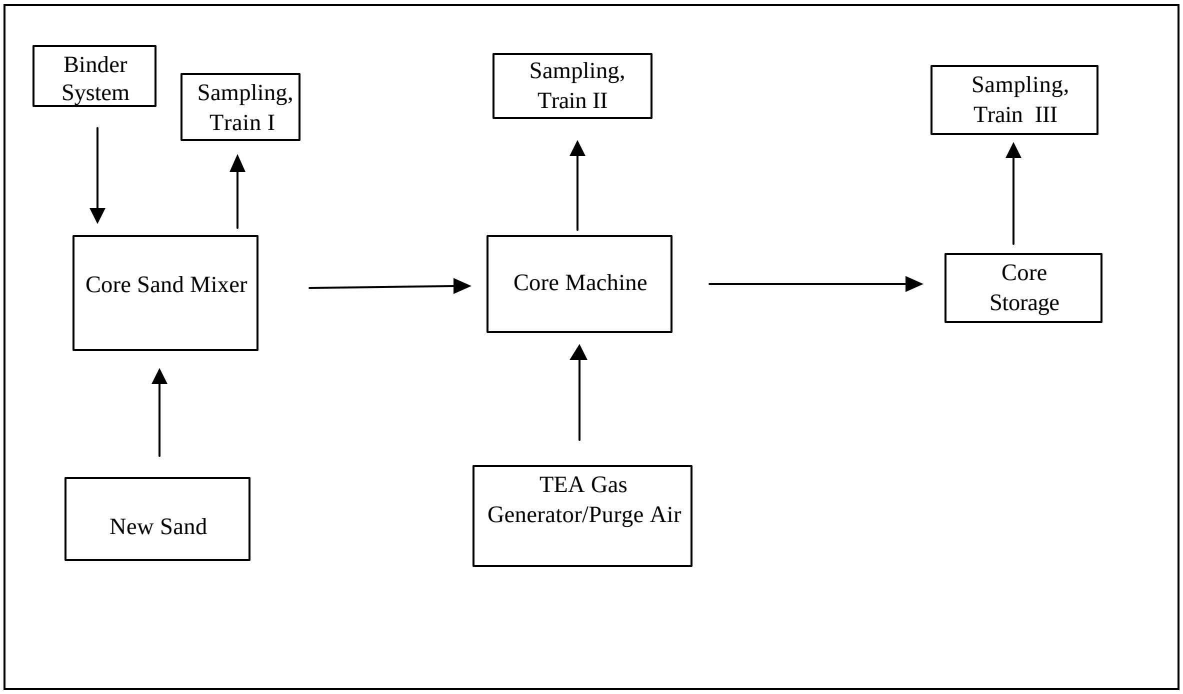
2.0 Test Methodology

2.1 Description of Process and Testing Equipment

Figure 2-1 is a diagram of the Phenolic Urethane Cold box core making process and testing equipment.

Figure 2-1 Core Making and Testing Process



2.2 Description of Testing Program

The specific steps used in this sampling program are summarized below:

1. <u>**Test Plan Review and Approval**</u>

The proposed test plan was reviewed by the Technikon staff and the CERP Steering Committee, and approved.

2. Preliminary Characterization of the Mixing Process

The Carver core sand mixer is a fifty (50) pound capacity paddle type mixer having a twenty (20) inch diameter and thirteen (13) inch deep bowl with a cross-head rotating at about twenty-five (25) RPM. The working sand depth was 3-5 inches.

The mixer was covered with a transparent acrylic lid having a 4 inch hole through which all materials were charged. The hole had a swiveled cover that was kept closed at all times except when material was charged into the mixer. The cover was never removed from the mixer throughout the testing periods.

A 1/4 inch diameter heated sampling probe, connected to a vacuum driven sampling train, was inserted through the sidewall terminating at the center of the bowl one (1) inch below the cover. The cover was supported approximately 1/16th inch above the rim on the mixer bowl to supply makeup air in an inward radial direction to the sample probe. The gap between the cover and the mixer bowl allowed an inward radial air velocity sufficient to prevent emission escape.

The sampling rate, approximately one (1) actual cubic foot per minute (ACFM), was chosen to be the best balance for the mixer geometry, prevention of emission escape, the sampling period, the sampling train capacity to maintain stable critical orifice controlled flow, the sorbent collection tubes capacity, the analytic detection limits, and not disturbing the mixing process equilibrium by the sampling activity. A Dräeger smoke tube was used to verify that the above criteria were satisfied.

The mixer was provided with an environmental enclosure consisting of an open topped, full height, 4 sided, 1-inch thick aluminum foiled-faced-urethane insulated box continuously flushed with clean temperature controlled air. A perimeter-sealed hole in the side of the enclosure allowed discharge of the mixed sand through the enclosure to the core machine supply hopper.

The mixer cycle time was chosen at seven (7) minutes so that a fifty (50) pound batch would continuously support the core making machine, making a nominal 7.25 pound core at a nominal one (1) minute cycle time, and have no core blower machine delays. Preliminary testing of the mixer cycle time was varied to explore emission characteristics.

The mixer system was instrumented with thermocouples to measure the temperatures of the room ambient air, the mixer ambient air, headspace (probe) air, the mixer bowl steel bottom, and the sand.

Sand batches were mixed with 1.4% (BOS) Ashland 305/904 binder in a 55/45 ratio of Part I resin and Part II co-reagent.

Figure 2-2 Mixer with Attached Sample Train.
(The environmental enclosure is not shown here).

3. Establishing Equilibrium for Emission Measurement

US EPA Method 25A (TGOC) was chosen as the method to monitor the mixing process using a California Analytics total hydrocarbon (THC) analyzer. In the absence of other driving forces, evaporation was assumed to be the mechanism driving all emissions. During this test, measurements were taken to demonstrate the influence of process variation on the evaporation events.

The literature defines how liquid evaporation functions. Anything that raises the liquid vapor pressure like temperature, increases apparent surface area like mechanical stirring, or enhances energy transfer to the liquid surface to promote the liquid-vapor phase transformation like air movement or temperature enhances evaporation.

Sources of temperature change: The emissions come from the thin coating of organic binder on the sand. Because the coating is thin, the coating temperature is very close to the surface temperature of the sand grains. Therefore that which can cause the sand to change temperature influences emissions.

Gear box mechanical heating: Chart 1 demonstrates that the heat generated in the mechanical gear box finds its way up into the mixing bowl and into the headspace air of the mixing chamber and into the sampling manifold. The bowl bottom temperature is always hotter than the headspace which establishes the direction of heat flow. The mixer bowl heating rate is approximately 1°F per seven minute cycle from this source.

Sand frictional heating: Chart 2 demonstrates that the sand is heated while mixing. The rate of temperature increase for the mixer bowl is about three times greater when sand is in the mixer than when the mixer is empty. The headspace, which is now separated from the bowl by the sand, heats at a rate about four times faster with sand in the mixer than when empty, Hence, the sand must be hotter than the bowl. If the sand were hotter than the bowl when charged this could temporarily account for the faster bowl and headspace temperature rise. Since the sand has the highest heating rate of the three there must be a net gain of heat into the sand which can only come from frictional heating of the sand rubbing on itself under its own load driven by the mixer. At the same time, the sand load will increase the heat from the mixer motor and gears into the bowl. The sand temperature rise rate is approximately 3°F per seven minute cycle. See Chart 1 for temperature rise in an empty mixer. See Chart 2 for temperature rise in sand filled mixer.

Chart 1 Temperature Rise in Empty Mixer

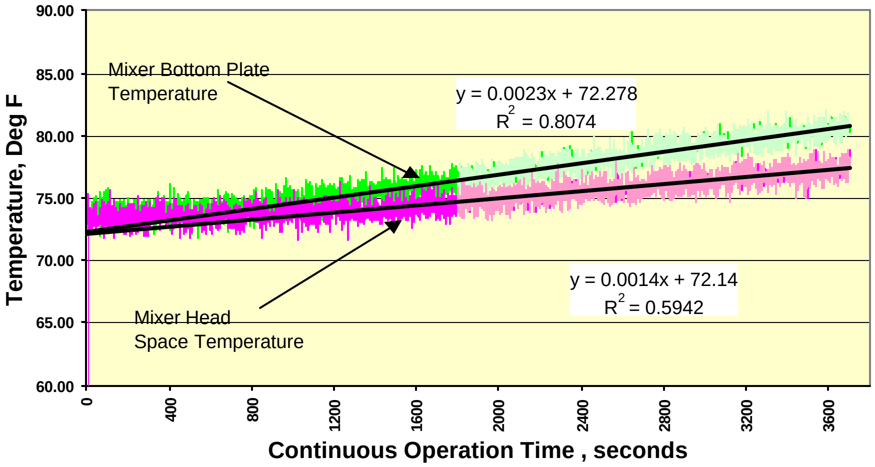
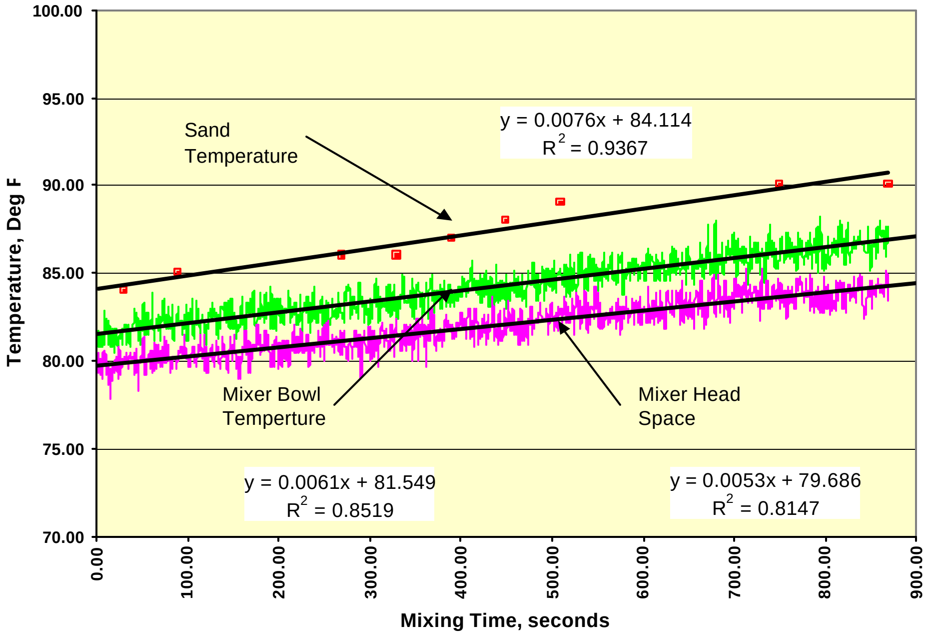


Chart 2 Temperature Rise in Filled Mixer



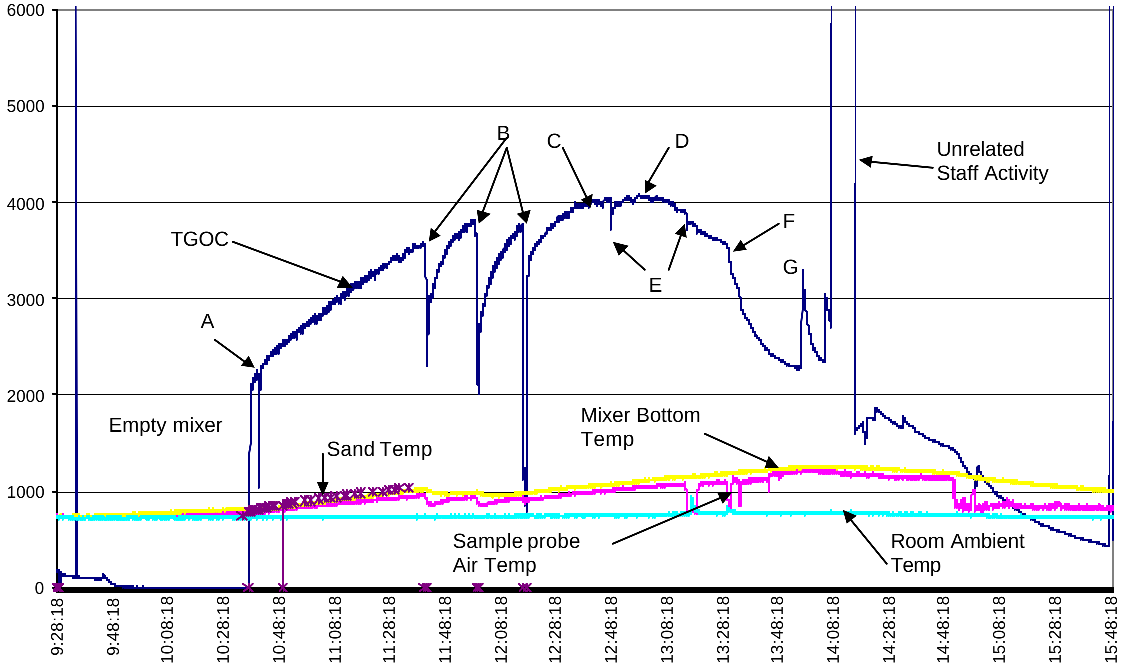
All the temperature increases continue far beyond the cycle time of the mixer. Therefore equilibrium can never be reached unless the mixer bowl temperature exceeds the ambient mixer air temperature by a sufficient amount to increase heat losses. The amount of ambient air flowing around the bowl removes the static layer of air insulating the mixer and carries more heat away. The volume of air drawn through the sampling manifold also affects the muller headspace temperature.

In the end, adjustment of the air flow velocity around the mixer led to the most stable sand temperature and resulting emission rate.

4. Mixer Characterization

On Chart 3 the vertical scale is PPMV for TGOC and ten (10) times the Fahrenheit temperature for all temperature measurements. The horizontal scale is clock time.

Chart 3 EU Pretest Mixer Characterizations



Points on Chart 3 (A through G) are explained below:

A. Binder sand at 74°F had just been charged into the 80°F mixer bowl. The mixer was stopped, the lid opened to flush the emissions out, then re-closed and re-started. The rapid re-establishment of the emission concentration, 37% of the deviation in 5 seconds and 100% in 38 seconds, demonstrate that changes accompanying materials introduction would reflect the condition of those materials and not the time for the mixer bowl to fill with emissions. The sand temperature remained at approximately 74°F until after the emission concentration had been re-established.

The gradual rise in concentration reflects the equilibrium vapor pressure of the binder solvents with the binder's liquid surface that is temperature controlled by the sand temperature. The sand temperature gradually rose due to frictional heating reaching 104°F at the time of discharge. Other experiments have demonstrated that the total solvent emissions from mixing are only 5-10% of the total available solvent emissions from the core binder. Therefore the binder solvents can be considered as a long-term emission source for the purpose of the mixing portion of this experiment.

B. Discharge of the 1st, 2nd, and 3rd batches. Recharge of the 2nd, 3rd, & 4th batches. The sand and mixer bowl temperatures had risen to 104°F due to frictional heating. The sharp decline in emissions prior to point B reflects the dilution effects from replacement of the sand bulk volume with an equivalent volume of uncontaminated ambient air and reduction in vapor pressure from introduction of sand and ambient air having colder temperatures. The deepening of the drop after each successive discharge reflected the length of time between discharge and recharge. The recharge interrupts the concentration fall during discharge. The gradual rise in emission concentration after the re-charge reflects the gradual rise in sand temperature from heat exchange between the 104°F mixer bowl and the new 74°F sand as well as some frictional heating during the approximately eighteen (18) minute cycle. Each cycle takes a little longer to recover as the excess heat is extracted out of the mixer bowl by successive sand charges until a maximum emission concentration within a cycle is achieved. A shorter cycle than the seven (7) minute cycle actually used would see a smaller concentration swing.

C. The mixer environment was changed by flooding the immediate area of the mixer with flowing 90°F air. This action created increased heat transfer to extract enough heat from the mixer bowl that the sand temperature rise was abated and the emission concentration stabilized.

D. A portable fan was directed at the mixer displacing some of the 90°F air with 75°F air having greater velocity. More heat was extracted from the mixer and the sand temperature decreased along with the emissions concentration.

E. While the emissions were more stable the lid was removed and then replaced to see how sensitive the emission concentration was to such a disturbance. It was small compared to other disturbances.

F. Finally the lid was taken off so that the moving ambient air stirred up the air in the mixer. Dilution and cooling processes followed.

G. The vacuum to the sample train was turned off and the emission concentration subsided over the next hour and a half with a few disturbances by the test personnel.

5. The Final Configuration

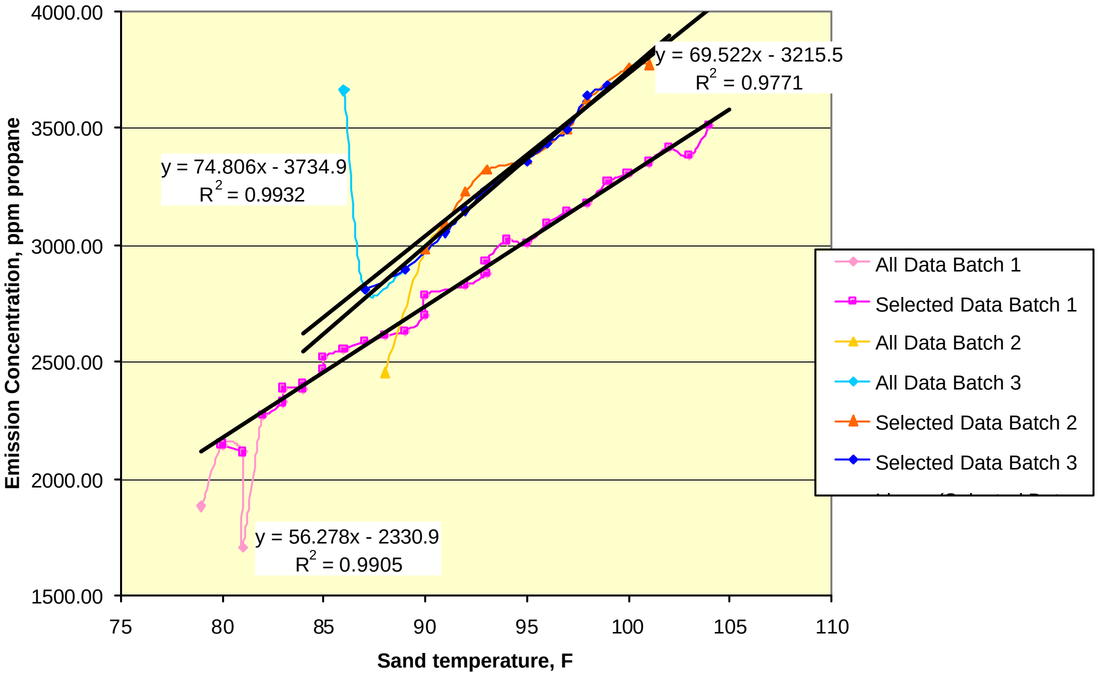
The lid was put on and left closed as much of the time as material additions permitted. The new sand and ambient mixer air temperatures were made to be nearly the same at about 80°F to minimize heat transfer during the test. The sampling rate was set at about one (1) ACFM except when that was a test parameter. The mixing test cycle time of seven minute, while long by commercial standards, limited sand heating to less than 4°F per cycle and the material flow rate matched the core making machine demand.

6. Relationship of Emissions to Sand Temperature

Chart 4 illustrates the relationship between emissions as TGOC and sand temperature for two conditions in the Carver mixer. The lower data is the first batch wherein 78°F sand was charged into a 74°F mixer. The upper data are batches 2 & 3 where 74 & 73°F sand was charged into a 107 and 101°F mixer respectively.

The trend lines indicate that the initial emission concentration from a 73-78°F sand was 1890, 1999, & 1875 PPMV respectively. The rates of incremental emission increase relative to the incremental sand temperature increase was dramatically greater when cold sand was charged into the same hot mixer at all sand temperatures, 70-75 vs. 56 times the sand temperature increase. This outcome results directly from the mixer transferring heat to the sand. The reverse would be true if sand were charged into a colder mixer. The outliers at the beginning of each batch reflect the first contact between binder solvents and the mixer bowl. The trend lines do not include these outliers. The equilibrium relationship is closer to the lower data because during repeated use the new charged sand and the mixer will become closer to the same temperature.

Chart 4 TGOC Emission Concentration vs. Sand Temperature for 1.4% Binder Sand



7. Impact of Sampling Rate or Mixer Ventilation Rate

The mixer was allowed to temperature stabilize before testing began.

Emission Profile: Chart 5 illustrates the shape of the individual cycle emissions as TGOC concentration at three (3) discreet air sampling flow rates. It is apparent that the small differences in the sample rate relative to the mixer volume impact not only the numeric value of the emissions but the delicate temperature balance existing within the mixer. As the sample rate increases dilution reduces the numeric value of the emission concentration. The shape of each curve suggests that the emission is occurring faster than the air extraction rate in all but the highest sample collection flow rates. At 4.0 ACFM the emission concentration was steady throughout each cycle. In Chart 5 all temperatures are represented at ten (10) times their actual value.

Chart 5 TGOC Emission Concentration vs. Sample Flow Rate

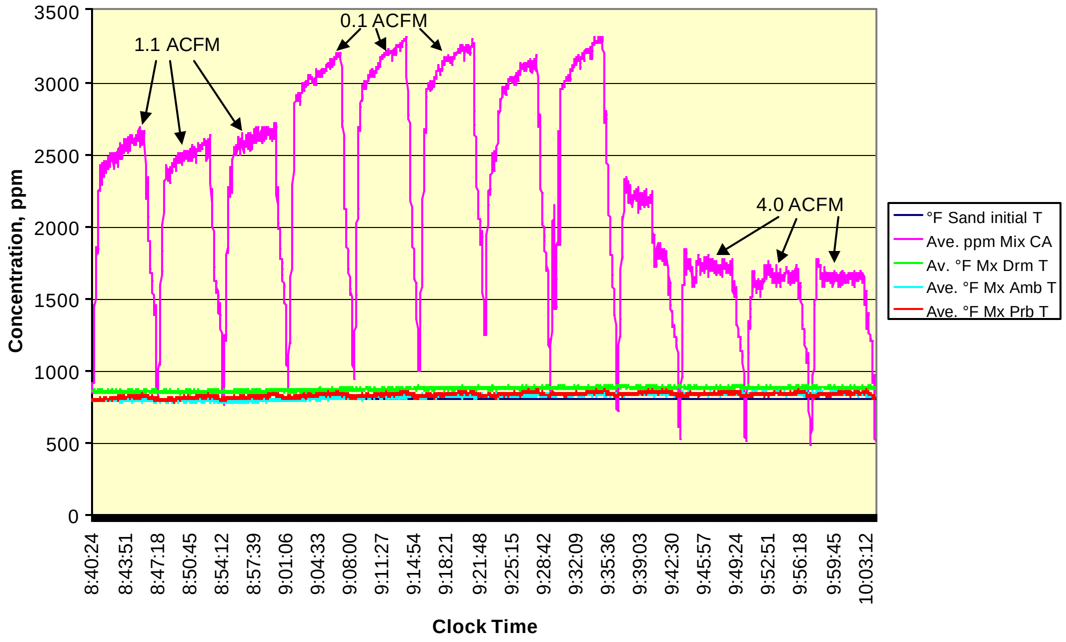
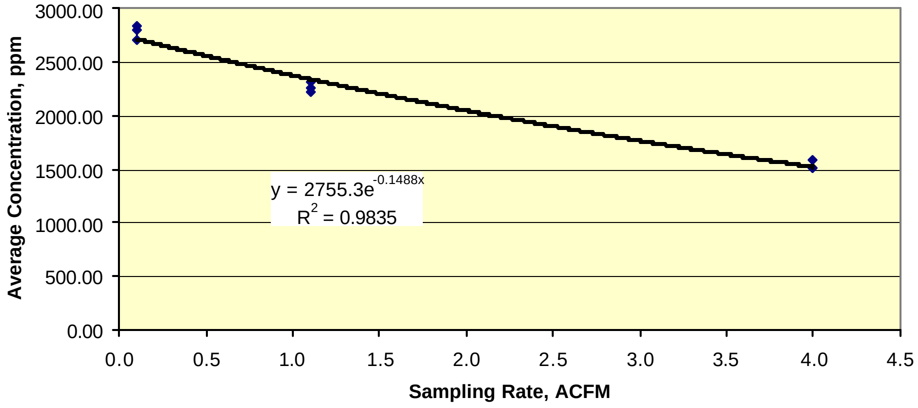


Chart 6 shows the average concentration vs. sample flow rate.

Chart 6 Average Mixing TGOC Emission Concentration vs. Sampling Rate



The concentration variation due to sample flow rate was an issue in the testing only because the sample rate was also the air ventilation rate through the muller.

8. Impact of degree of mixer filling

The mixer temperature was allowed to stabilize before testing began. Mixing at constant machine speed has the effect of varying the exposed surface area of the granulated sand. The sand was moving also so there is some component of increased evaporation relative to a static body of sand having the same surface area. All of the tests in this group were conducted at the same machine speed so only changes in apparent exposed surface should influence the emissions outcome. This mixer has both horizontal and vertical directing veins.

As shown in Charts 7 and 8 it is apparent that the degree of mixer fullness does influence the emissions rate. The emission concentration will adjust to a different equilibrium where the generation and extraction rate balance. Increased loading of the mixer does not increase emissions in an unbounded manner. There is a maximum for each geometric design beyond which the tools of the machine become buried and increase the apparent exposed area less and less. Eventually the tools get buried so deep that the sand mass approaches a stationary configuration as if the mixer were not moving. In this muller the maximum occurred at a sand depth of 75-80% of the highest horizontal tool height. This depth may also be the depth of optimal mixing efficiency for this machine.

Chart 7 TGOC Emissions vs. Mixer Sand Load

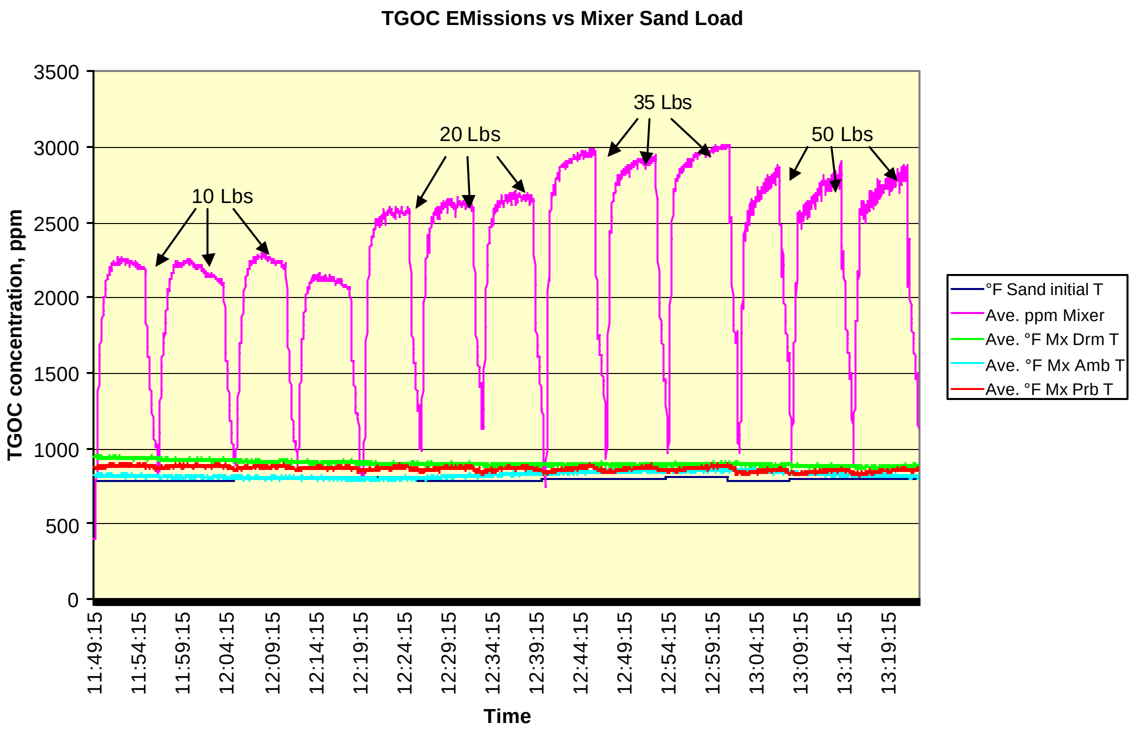
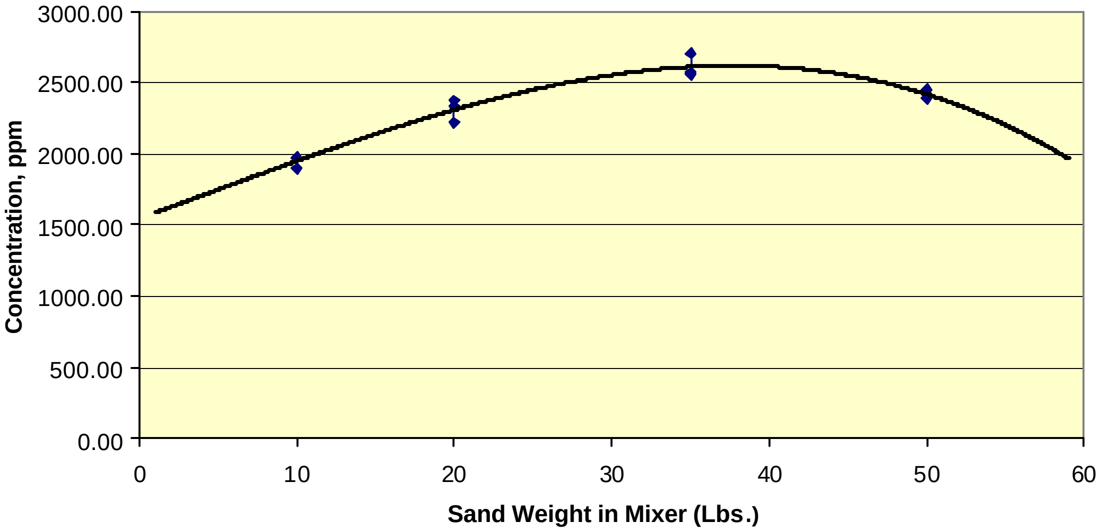


Chart 8 TGOC Emissions vs. Mixer Fill



9. Impact of Ambient air Temperature

In points C & D of Chart 3 on mixer characterization, the ability of the sand temperature and thus the emissions to come to equilibrium was explained to be partially dependent on the influence that the mixer's ambient temperature had on the heat distribution in the mixer. Looking at that subject in more detail now, when the mixer's ambient temperature is held constant at two different values and the sand initial temperature is the same, the emissions, as shown in Chart 9, increase with the mixer ambient temperature. Closer scrutiny in Charts 10 & 11 reveal that when the initial sand temperature of each batch is held constant and the mixer ambient temperature is held constant throughout each run, the emissions still vary. Chart 11 reveals that the emissions are following the real sand temperature which is the real-time binder solvent temperature.

The differences between the plotted curve shapes of the individual mixer batches in Chart 10 and 11 is that in Chart 10 eighty (80) degree Fahrenheit sand is being put in a mixer that is initially at sixty-four (64)^{o}F which is the mixer ambient temperature but in Chart 11 eighty (80) degree sand is being put in a ninety (90)^{o}F mixer which is its ambient temperature. As can readily be seen throughout Chart 10 the sand is initially chilled to the current mixer bowl temperature and incrementally heating the mixer bowl until a balance is struck between the 80^{o}F source of each new batch and the constant extraction of heat to the 64^{o}F ambient. Then the constant generation of heat from the gears and sand friction tip the balance to a gain of sand temperature and resulting emissions. In Chart 11 the same situation is being approached from the opposite end. Eventually these two extremes will find their end points somewhere between the emission extremes shown. So the role of the mixer ambient temperature is to regulate how the sand dissipates the heat gained from friction and the gears and motor.

Chart 9 TGOC Emissions vs. Mixer Ambient Temperature

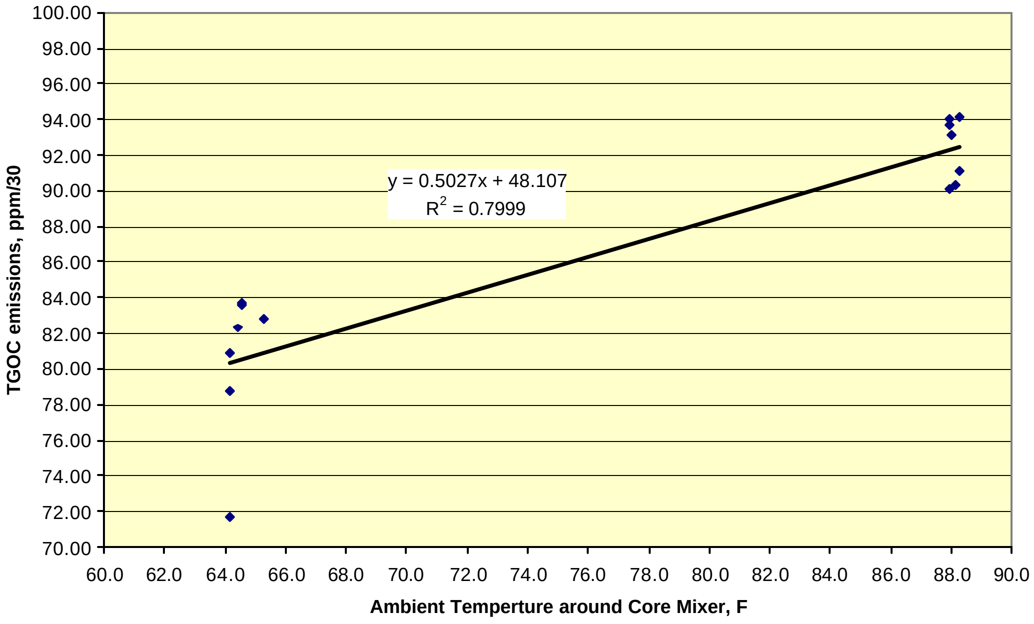


Chart 10 TGOC Emission Concentration for Ambient 63-65°F Air and Initial Sand Temperature 80-82°F

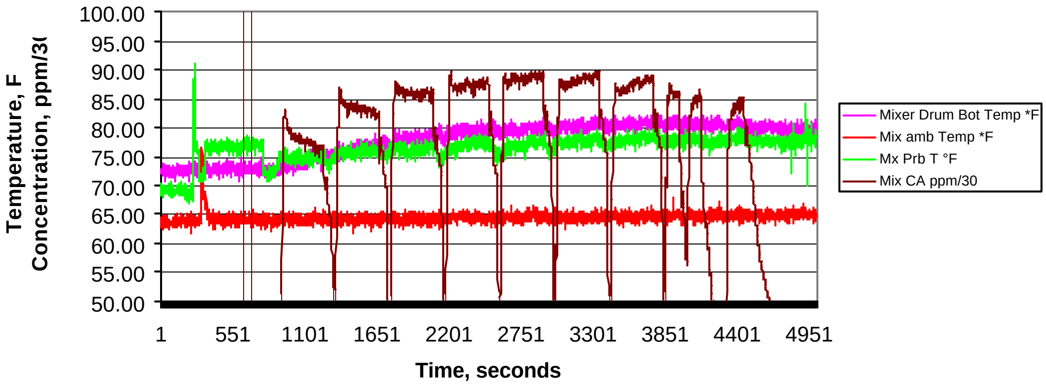
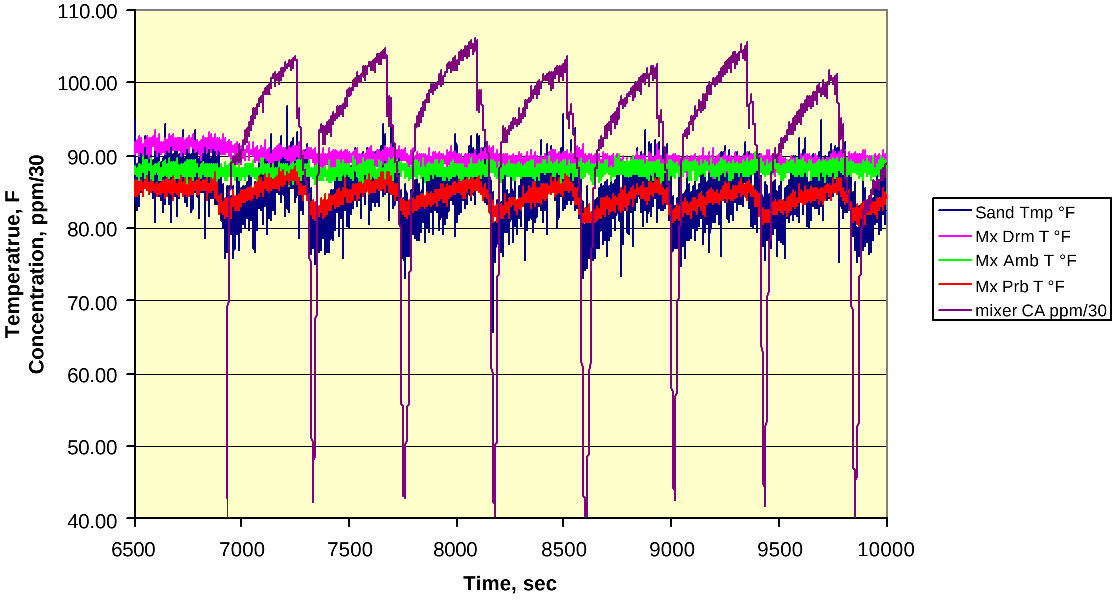


Chart 11 **TGOC Emission Concentration for Ambient Air 87-88°F and Initial Sand Temperature 80-82°F**



10. Impact of mixing speed on mixing emissions.

The mixing process includes all three physical parameters influencing evaporation: Temperature, effective exposed area, and air movement over the binder liquid surface. Changes in mixer speed can alter all three of these parameters. The mixer heats the sand by friction, distorts the at-rest shape of the sand with its tools, and pushes the sand around in its bowl which has the same effect as air moving over the sand surface.

This speed test was done in a Simpson Technologies 275 pound variable speed mixer. The mixer has a 20 inch diameter by 25 inch deep mixing bowl; a 200 pound batch containing 1% (BOS) Phenolic urethane core binder. The at-rest depth of the sand in the mixer bowl is about 11 inches. The mixer was run at 280 and 1700 RPM. The sand began in all of this series tests at 71-73 degrees Fahrenheit. The end temperature was quite different, 78-80°F at low speed and, 126-128°F at high speed, after only 2 minutes of mixing. The velocity that the sand moved around the mixer and therefore the relative air velocity over the sand was not measured but is likely in proportion to the spindle RPM. The degree to which the sand is air borne at these two speeds and therefore the amount of relative surface exposure is not known. It could have been fully air borne at both speeds.

Chart 12 illustrates the relative emissions at the two speeds. Chart 13 shows the same emission data in terms of the sand temperature resulting from mixing speed. Comparing the slope of this chart (116 ppm/deg F) to Chart 4 (56 ppm/deg F), done at 25 RPM, suggests that an increased amount of the emissions at higher speed do come from greater sand surface area exposure and relative air velocity in addition to the sand temperature.

Chart 12 TGOC Emission Concentration vs. Mixer Speed

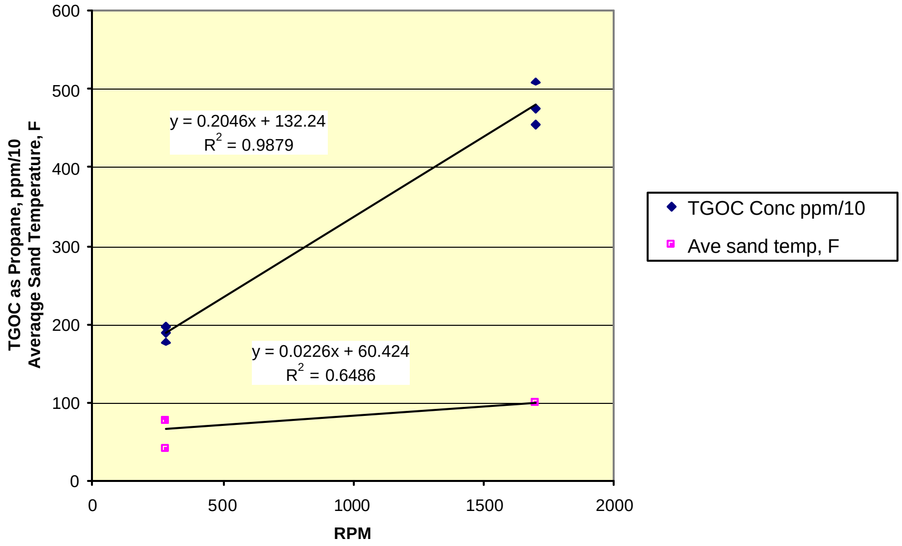
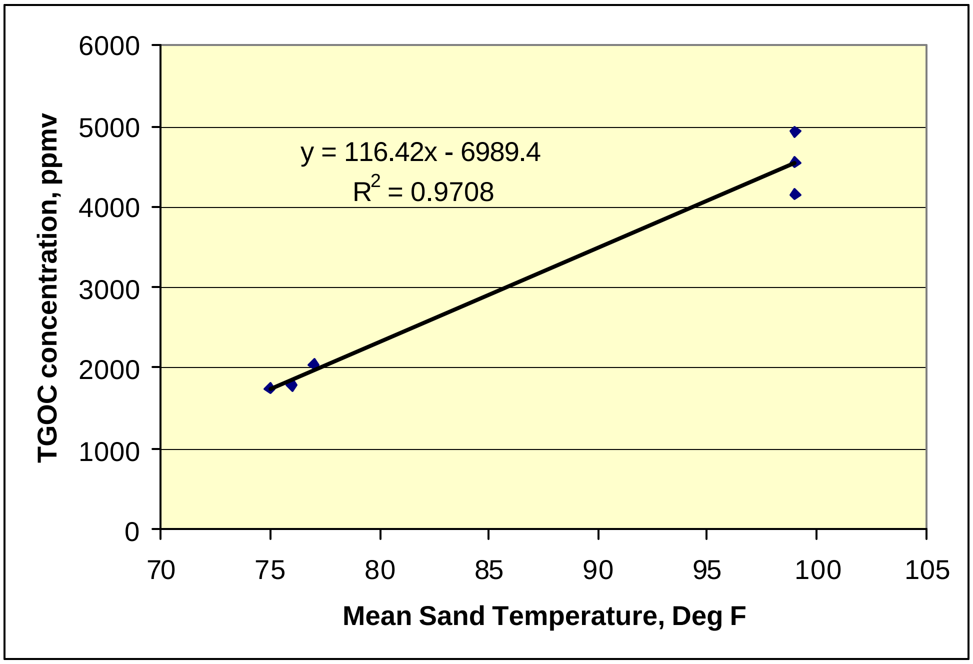


Chart 13 TGOC Emission Concentration vs. Mean Sand Temperature Resulting from Mixing Speed



11. Impact of sand type (mean grain size) in mixing emissions

Sands come in different densities and size distributions. The amount of surface area available for evaporation per pound or unit volume is different. Chart 14 shows the TGOC emission profiles from fifty (50) pound mixing batches of three (3) sands having average grain sizes (GFN) of 50 (Wexford W450 Lakesand), 70 (Amador A-70 silica sand), and 95 (US silica F-95 silica sand. Chart 15 shows the average TGOC emission concentration over the cycle. Chart 16 shows the same data when the small temperature differences are corrected to a common temperature of 77 °F using the regression equation from chart 4.

Chart 14 TGOC for Sands with Different Particle Sizes

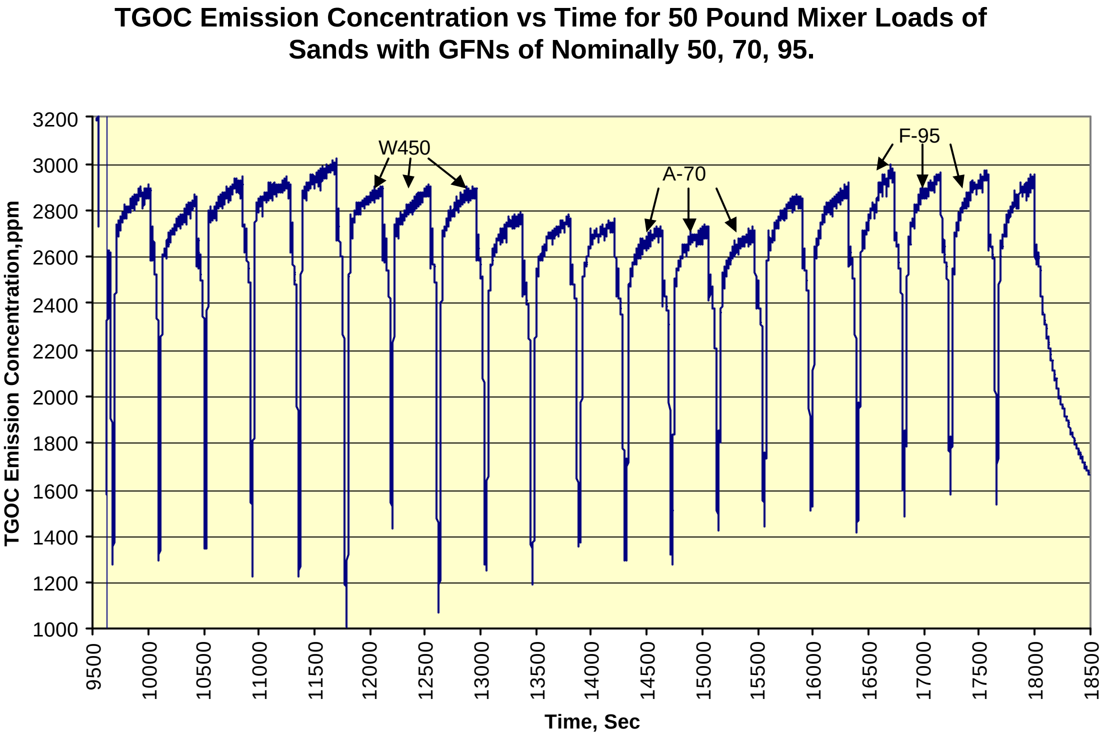


Chart 15 TGOC Emission Concentration vs. Mean Particle Size

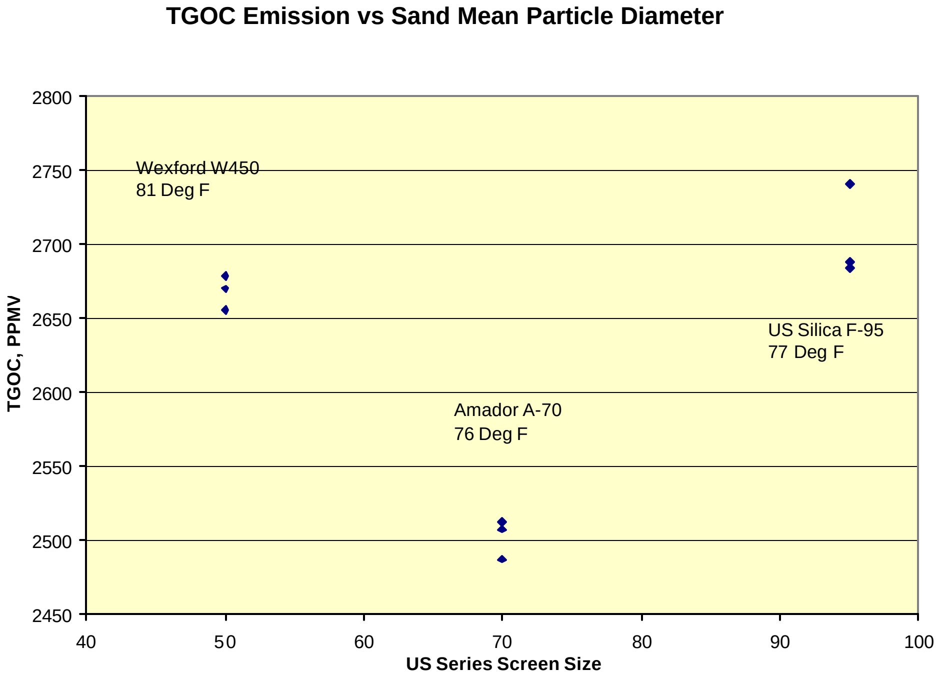
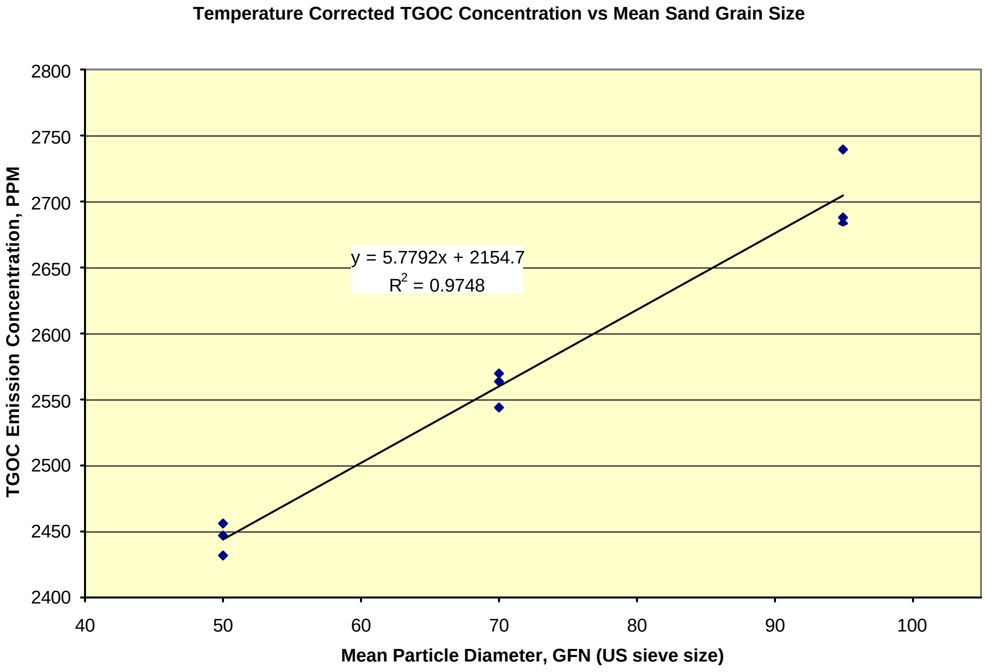


Chart 16 TGOC Concentration vs. Mean Particle Size Corrected for Temperature



12. Impact of binder content on mixing emissions

Mixing spreads the binder into a thin film over the sand. Once the sand is all coated changes to the amount of binder, within reasonable limits, only change the thickness of the film but does not significantly change the surface area for evaporation. Chart 17 & 18 Show the TGOC emission profiles for 50 pound batches of sand mixed at 25 RPM and 80°F sand temperature. Chart 19 compares the emissions resulting from 50 pound sand batches containing 1.0 & 1.75% binder. The batches were mixed using 80°F sand that discharged uniformly at 90°F into 70 ambient air.

Chart 17 TGOC Emission Profile for 1% binder at 80°F & 25 RPM

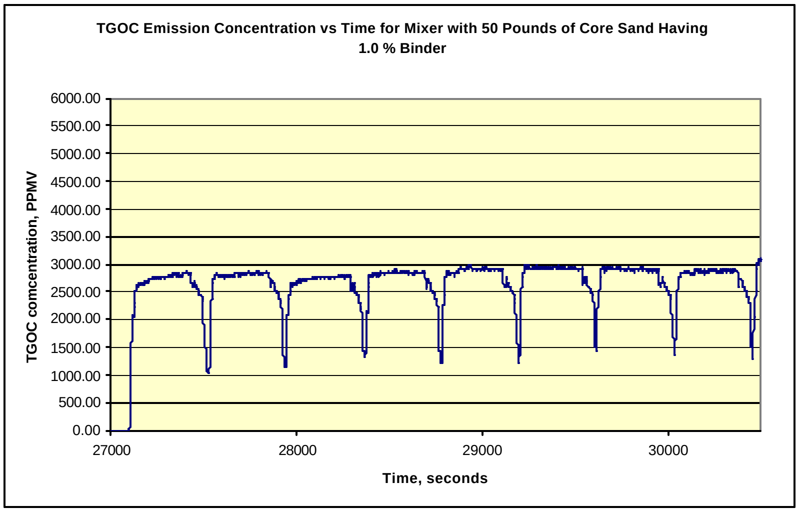


Chart 18 TGOC Emission Profile for 1.75% Binder at 80°F & 25 RPM

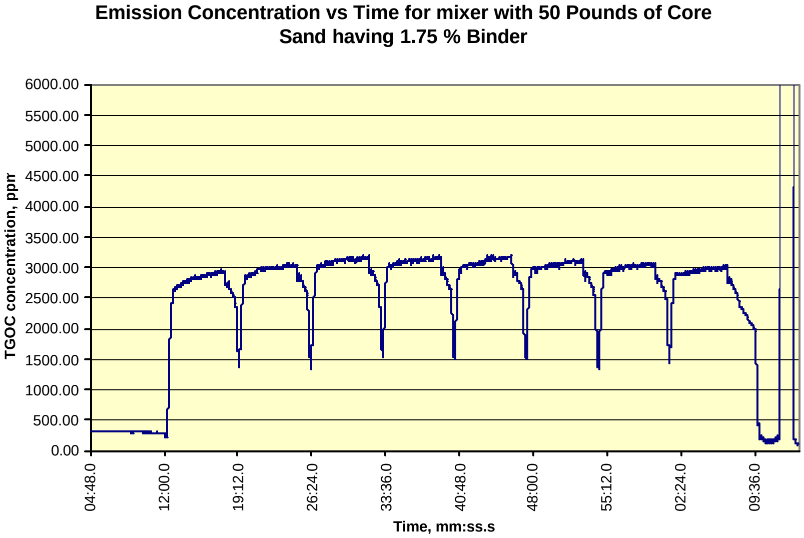
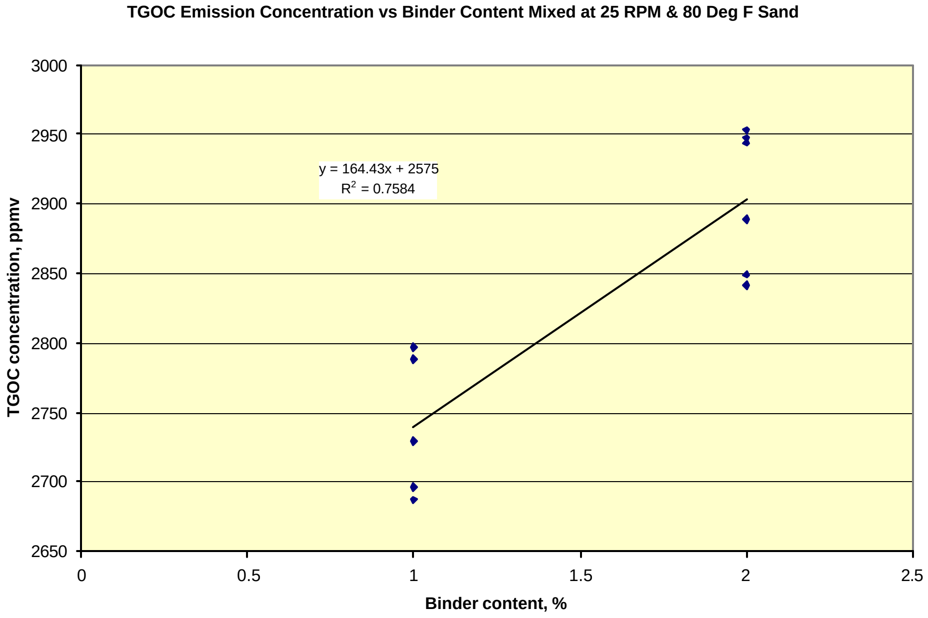


Chart 19 TGOC emission vs. Binder content at 80°F and 25 RPM



3.0 Discussion of Results

The testing concluded that air emissions from PU binder systems during core sand mixing are the result of evaporation of the solvents in the resins. The mixing process includes all three physical parameters influencing evaporation: temperature, effective exposed surface area, and air movement over the surface of the coated sand grains. Binder content and sand type also influence emissions. To minimize these emissions control of sand temperature is the most important process variable. Selection of mixer type and speed as well as ambient air temperature and movement impact the amount of heat build up in the sand. The mixer type and speed also impact the amount of sand surface exposed for evaporation

Summary of relation ships between the variable affecting the emission from the mixing process.

Variable	Equation	Correlation Coefficient R^2
Sand Temperature (F) vs. Mull Time (sec)	Y = 0.0076 X + 84.114	0.94
TGOC Conc. (PPMV) vs. Sand Temp. @ 25 RPM	Y = 69.522 X – 32.15.5	0.99
TGOC Conc. (PPMV) vs. Mixer Ventilation Rate (l/min) @ 25 RPM	Y = 2755.3 EXP(-0.1488 X)	0.98
TGOC Conc. (PPMV) vs. mixer Load	Maximizes at 75% of rated capacity	N/A
TGOC Conc. (PPMV) vs. Ambient Air Temp (F) @ 25 RPM	Y = 0.5027 X + 48.107	0.80
TGOC Conc. (PPMV) vs. Mixer Speed 280-1760 RPM	Y = 0.2046 X + 132.24	0.99
TGOC Conc. (PPMV) vs. Sand Temp (F) 280-1760 RPM	Y = 116.42 X – 6989.4	0.97
TGOC Conc. (PPMV)vs. Particle size (GFN)	Y = 5.7792 X + 2154.7	0.97
TGOC Conc. (PPMV) vs. Binder Content (%)	Y = 164.43 X + 2575	0.76

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APPENDIX A APPROVED TEST PLAN FOR TEST EU

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TECHNIKON TEST PLAN

> **CONTRACT NUMBER:** 1409 **TASK NUMBER:** 1.3.1

> **WORK ORDER NUMBER**: 1169 **Series:** EU

> **SAMPLE EVENTS:** 8 TGOC preliminary,9 mix, 51 make , 17 store TGOC & tubes

> **SITE: ___PRE-PRODUCTION(243) _X__ FOUNDRY(238)**

> **TEST TYPE:** Core mixing, core making, core storage. Process variables study**.**

> **METAL TYPE:** None

> **MOLD TYPE:** None

> **NUMBER OF TESTS**: 5 Preliminary, 9 core sand mixing, 17 core making with scratch hardness, 17 core storage, all in triplicate.

> **CORE TYPE:** AFS Step Core, Ashland ISOCURE® 305/904 phenolic urethane binder at 1.0% and 1.4% and 1.75% total resin, 55% Part I, 45% part II, TEA gas catalyzed.

> **TEST DATE:** **START**: 4 Nov 2002
> **FINISHED:** 12 Dec 2002

TEST OBJECTIVES:

1. Measure VOCs and HAPs from Core Mixing, Core Making & Core Storage by the methods established in the **Core Mix, Make, & Store Baseline 2002** from a regiment of tests in each venue which explore the range of process variation normally encountered in commercial foundry practice.

VARIABLES:

1. **Preliminary Tests**: The first tests will include a battery to outline the process sensitivity to the operating environment and define a stable region of testing. This series will include heat gain from gear and sand friction, emission sampling rate, environmental temperature, and mixer fullness for each condition.

2. **Core Sand Mixing:** The Mixing parameters will include sand GFN, sand temperature, binder concentration, and mixing speed. The reference uncoated sand shall be Wexford W450 Lakesand. It shall be preheated or cooled to a reference temperature of 80 +/-2 degrees Fahrenheit. The reference binder concentration shall be 1.4 +/-0.014% Ashland ISOCURE® 305/904 mixed Part I/Part II in the ratio of 55/45. The sand will be coated in a Redford/Carver 50 pound core sand mixer for 7 minutes. One minute shall be used to

dispense the sand and the two binder components and one additional minute shall be used strictly for discharging the mixer. Each core sand-mixing test shall be three (3) seven (7)-minute 50 pound cycles, monitored continuously by TGOC and adsorption tubes. Prior to the first mixing test five (5) batches shall be run to normalize the background within the muller. Sampling media will be changed after each three-cycle test during which time mixing will continue in order to maintain the background concentration. A total of three (3) mixing cycles shall be run at each of 3 parameter levels for each variable.

3. **Core Making:** The Make tests will each include effects of sand temperature, binder content, blow time, blow pressure, purge pressure, purge air temperature, purge duration, & sand GFN with sand mixed to a standard duration, sand temperature, binder content, and/or ambient (enclosure) air temperature as called out in the attached test plan tables. Make tests will include scratch hardness testing at 2 hours age The Redford/Carver core machine will operate on a nominal one (1) minute door-to-door cycle. The environmental enclosure shall be supplied with air controlled to 82 +/- 5 degrees Fahrenheit. TEA will be fed to the core machine at a nominal 5 grams per cycle. The reference purge pressure shall be 45+/-2 psi for 20 seconds. Reference blow pressure shall be 30 psi. The core-make test will begin after the core machine has run sufficient time, at rate, to have the background emission concentration stabilize. Each core-make test will be 30 core cycles, about one half hour long, with continuous TGOC and adsorption tube sampling. Sample media will be changed after each 30 cycle test. The core machine will run continuously during media change and testing to maintain the background concentration. The gas & purge and fugitive emissions will be collected to a common sampling stack. Each core will be weighed.

4. **Core Storage**: The storage test will consist of weighed cores sequentially sampled, four (4) in a group, from the core machine during the make test and placed in individual sampling domes. The domes are in a temperature controlled room at 82+/-5 degrees Fahrenheit and sampled continuously with TGOC and adsorption tubes for 1.5 hours.

BRIEF OVERVIEW: Core making is not a single process but rather a series of steps each with its own process collectable and fugitive emissions. This test will look at selected HAP & VOC emissions from combined process collectable and fugitive emission streams during each of the core sand mixing, core making, and core storage steps. Each step will have a series of parameters varied per the attached test plan tables while all other controllable parameters are held in reference value ranges.

SPECIAL CONDITIONS: The sand mixer will have a removable lid that allows air to infiltrate radially from the perimeter. Materials will be charged though a closeable door in the lid. Samples will be extracted from the center of the headspace below the lid. The mixer shall be surrounded on 4 sides with an insulating wall that extends 3 inches above the mixer to reduce room ambient influences. The enclosure shall be flooded with air controlled to the reference temperature range. The emission samples shall be extracted at a reference rate.

The core machine with step core tooling shall be housed in a double walled emission enclosure. The area between the walls shall be flushed with temperature controlled air at 82+/-5 degrees Fahrenheit. This air shall be the ambient make up air for the core process within the enclosure. The core box and core machine shall be tightly plumbed to extract gasses passed through the core box into a common sampling stack with the fugitive gasses. The sampling environment will be maintained at 75-85^{o}F. Core storage will be individual cores tested under individual glass domes in groups of four (4) cores for a period of 1.5 hours. The environment will be totally captured. One dome will be monitored by TGOC.

Original Signed	
Process Engineering Manager (Technikon)	**Date**
Original Signed	
V.P. Measurement Technology (Technikon)	**Date**
Original Signed	
V.P. Operations (Technikon)	**Date**
Original Signed	
Test Design Committee Representative	**Date**
Original Signed	
Emission Committee Representative	**Date**

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APPENDIX B SUMMARY TABLES FOR CHART DATA

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Summary Emissions vs Sand Temperature at 25 RPM provides Detail for Chart 4

Batch 1		Batch 2		Batch 3	
Sand Temp	Concentr.	Sand Tem	Concentr.	Sand Tem	Concentr.
F	PPM	F	PPM	F	PPM
78	20.52	88	2454.9	86	3661.0
79	1883.50	90	2982.3	87	2809.5
80	2147.20	91	3093.5	89	2896.1
81	2114.20	92	3227.6	91	3054.2
81	1707.70	93	3319.6	92	3148.6
82	2269.00	95	3367.1	93	3234.6
83	2327.20	97	3498.4	95	3358.6
83	2386.60	98	3623.3	96	3433.5
84	2386.00	100	3756.8	97	3492.6
84	2408.60	101	3772.3	98	3637.3
85	2466.60			99	3679.1
85	2518.00				
86	2556.30				
87	2587.40				
88	2612.70				
89	2630.40				
90	2698.90				
90	2787.00				
92	2826.00				
93	2877.80				
93	2932.00				
94	3019.80				
95	3006.10				
96	3089.50				
97	3142.50				
98	3179.40				
99	3271.10				
100	3307.70				
101	3353.10				
102	3413.70				
103	3379.30				
104	3508.20				

Summary for Sample Flow Rate details the data presented in Chart 6

Flow Rate ACFM	°F Sand Initial T	Ave. PPM Mixer	Ave. °F Mx Drm T	Ave. °F Mx Amb T	Ave. °F Mx Prb T	Ave. °F Deck Amb
1.1	78	2257.8	85.7	79.7	81.3	67.3
1.1	78	2217.8	85.6	79.2	81.3	67.0
1.1	78	2312.6	85.9	79.4	82.0	67.0
0.1	79	2708.3	86.6	80.8	83.0	67.6
0.1	82	2802.3	87.4	81.9	83.4	67.6
0.1	82	2839.5	87.9	82.5	83.7	67.6
4.0	81	1584.0	88.5	84.1	84.2	68.5
4.0	81	1510.6	88.4	84.4	84.1	68.4
4.0	80	1503.9	88.5	84.0	84.0	68.2

Summary for Mixer % Fill details data presented in Chart 8

Mixer Fill Lbs	°F Sand Initial T	Ave. PPM Mixer	Ave. °F Mx Drm T	Ave. °F Mx Amb T	Ave. °F Mx Prb T	Ave. °F Deck Amb	Ave. °F Room Amb
10	79	1896.67	93.83	81.85	88.49	79.77	69.28
10	79	1972.68	92.45	81.09	88.17	79.36	69.49
10	80	1975.52	91.38	80.57	87.66	78.96	70.27
20	80	2217.39	89.98	79.94	86.72	78.35	70.31
20	81	2374.00	89.50	81.28	86.75	79.79	70.52
20	79	2330.76	89.19	83.04	86.30	80.46	70.27
35	79	2553.74	89.12	84.15	86.37	80.92	70.71
35	80	2568.58	89.14	84.96	86.36	81.41	71.40
35	80	2704.70	89.53	85.51	86.96	81.69	70.68
50	79	2383.95	89.16	84.93	84.86	81.41	70.75
50	80	2414.83	88.31	83.02	84.70	80.43	70.85
50	80	2447.19	87.90	81.91	84.99	79.81	71.13

Summary Emisison vs Mixer Ambient Temperature Detail for Chart 9

Test No.	Ave. mixer	Ave. °F
18-Nov-02	ppm/30	Mx Amb T
P6.1a	71.70	64.2
P6.1b	78.72	64.1
P6.1c	80.94	64.2
P6.1d	82.29	64.4
P6.1e	83.70	64.5
P6.1f	83.60	64.5
P6.1g	82.83	65.3

Test No.	Ave. mixer	Ave. °F
19-Nov-02	ppm/30	Mx Amb T
6.2a	90.07	87.9
6.2b	93.99	87.9
6.2c	93.67	88.0
6.2d	93.15	88.0
6.2f	90.37	88.2
6.2g	94.14	88.3
6.2h	91.09	88.2

Summary Emission vs. Mixer Ambient Air Temperature Detail Data for Charts 10 and 11

Test No.	°F	Ave. mixer	Ave. °F	Ave. °F	Ave. °F	Ave. °F	Ave. °F
18-Nov-02	Sand initial T	ppm/30	Mx Drm T	Mx Amb T	Mx Prb T	Deck Amb	Room Amb
P6.1a	80	71.70	74.2	64.2	74.7	65.5	62.5
P6.1b	80	78.72	76.6	64.1	75.8	65.6	62.6
P6.1c	80	80.94	78.3	64.2	76.1	65.6	62.6
P6.1d	81	82.29	79.3	64.4	76.7	65.8	62.7
P6.1e	81	83.70	79.8	64.5	76.9	65.9	62.8
P6.1f	82	83.60	80.3	64.5	77.6	66.0	62.9
P6.1g	82	82.83	79.9	65.3	78.8	65.1	62.6

Test No.	°F	Ave. mixer	Ave. °F	Ave. °F	Ave. °F	Ave. °F	Ave. °F	Ave F
19-Nov-02	Sand initial T	ppm/30	Mx Drm T	Mx Amb T	Mx Prb T	Deck Amb	Room Aml	sand temp
6.2a	79	90.07	90.4	87.9	85.2	63.4	87.6	84.8
6.2b	80	93.99	89.7	87.9	84.7	63.4	87.5	84.7
6.2c	81	93.67	89.5	88.0	84.5	63.7	87.4	84.9
6.2d	80	93.15	89.3	88.0	84.2	64.0	87.2	84.4
6.2f	80	90.37	89.0	88.2	83.8	64.7	87.4	83.9
6.2g	80	94.14	89.1	88.3	83.9	65.0	87.4	84.0
6.2h	81	91.09	89.1	88.2	84.0	65.9	87.3	84.6

Summary Emissions vs. Mixer Speed Provides the Detail for Chart 12, 13.

Sample no.	EU108	EU109	EU110	EU111	EU112	EU113	Slow Average	Fast average
	Batch 2	Batch 3	Batch 4	Batch 6	Batch 7	Batch 8		
Mixer speed, RPM	280	280	280	1700	1700	1700		
Sand start temp, oF	73	72	72	----	----	71		
Start PPM	1634	1515	1677	4603	5238	4330		
Charge sand clock, hh:mm:ss	0:05:00	0:11:00	0:15:30	0:25:00	0:30:00	0:34:45		
Chg clock time part I finished, hh:mm:ss	0:05:45	0:11:30	0:15:56	----	0:30:28	0:35:10		
Chg clock time part II finished, hh:mm:ss	0:06:05	0:11:45	0:16:08	0:25:40	0:30:40	0:35:25		
After charge PPM	1483	1275	----	----	4811	4034		
Sample duration	3:00	2:00	2:00	2:00	2:00	2:00		
PPM @ 1 min after sand charge	1483	1425	1667	4196	4952	4319		
PPM @ 2 min after sand charge	2283	2186	2116	4030	4951	4783		
PPM @ 3 min @ discharge	2467	2427	2375	5369	5242	5591		
Sand end temp, oF	80	79	78	128	126	126		
Calculated Average sand Temp, oF	77	76	75	----	----	99	76	99
Average emission concentration, ppm	2041	1782	1754	4137	4929	4539	1859	4535

Summary Emissions vs. Mean Grain size Provides the Detail for Charts 15 & 16

Sand type	GFN	Average TGOC Concentration, ppm	Sand Temprature F	Temperature Corrected TGOC Conc. Ppm
Lake	50	2679	81	2455
Lake	50	2670	81	2446
Lake	50	2655	81	2431
Silica	70	2487	76	2543
Silica	70	2513	76	2569
Silica	70	2508	76	2564
Silica	95	2684	77	2684
Silica	95	2688	77	2688
Silica	95	2740	77	2740

Summary Emissions vs. Binder Content Provides Detail for Chart 19

Summary TGOC Concentration vs Binder %

	TGOC Concentration ppm	
Binder	1.00%	1.75%
Run 1	2518	2657
Run 2	2659	2824
Run 3	2598	2947
Run 4	2687	2953
Run 5	2729	2944
Run 6	2788	2889
Run 7	2797	2849
Run 8	2696	2841

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APPENDIX C GLOSSARY

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Glossary

ACFM	Actual Cubic Feet Per Minute
BO	Based on ( ).
BOS	Based on Sand.
HAP	Hazardous Air Pollutant defined by the 1990 Clean Air Act Amendment
HC as Hexane	Calculated by the summation of all area between elution of Hexane through the elution of Hexadecane. The quantity of HC is performed against a five-point calibration curve of Hexane by dividing the total area count from C6 through C16 to the area of Hexane from the initial calibration curve.
I	Invalid, Data rejected based on data validation considerations
NA	Not Applicable
ND	Non-Detect
NT	Not-Done, Lab testing was not done
POM	Polycyclic Organic Matter (POM) including Naphthalene and other compounds that contain more than one benzene ring and have a boiling point greater than or equal to 100 degrees Celsius.
PPMV	Parts Per Million by Volume
TGOC	Total Gaseous Organic Carbon
TGOC as Propane	Weighted to the detection of more volatile hydrocarbon species, beginning at C1 (methane), with results calibrated against a three-carbon alkane (propane).
VOC	Volatile Organic Compound