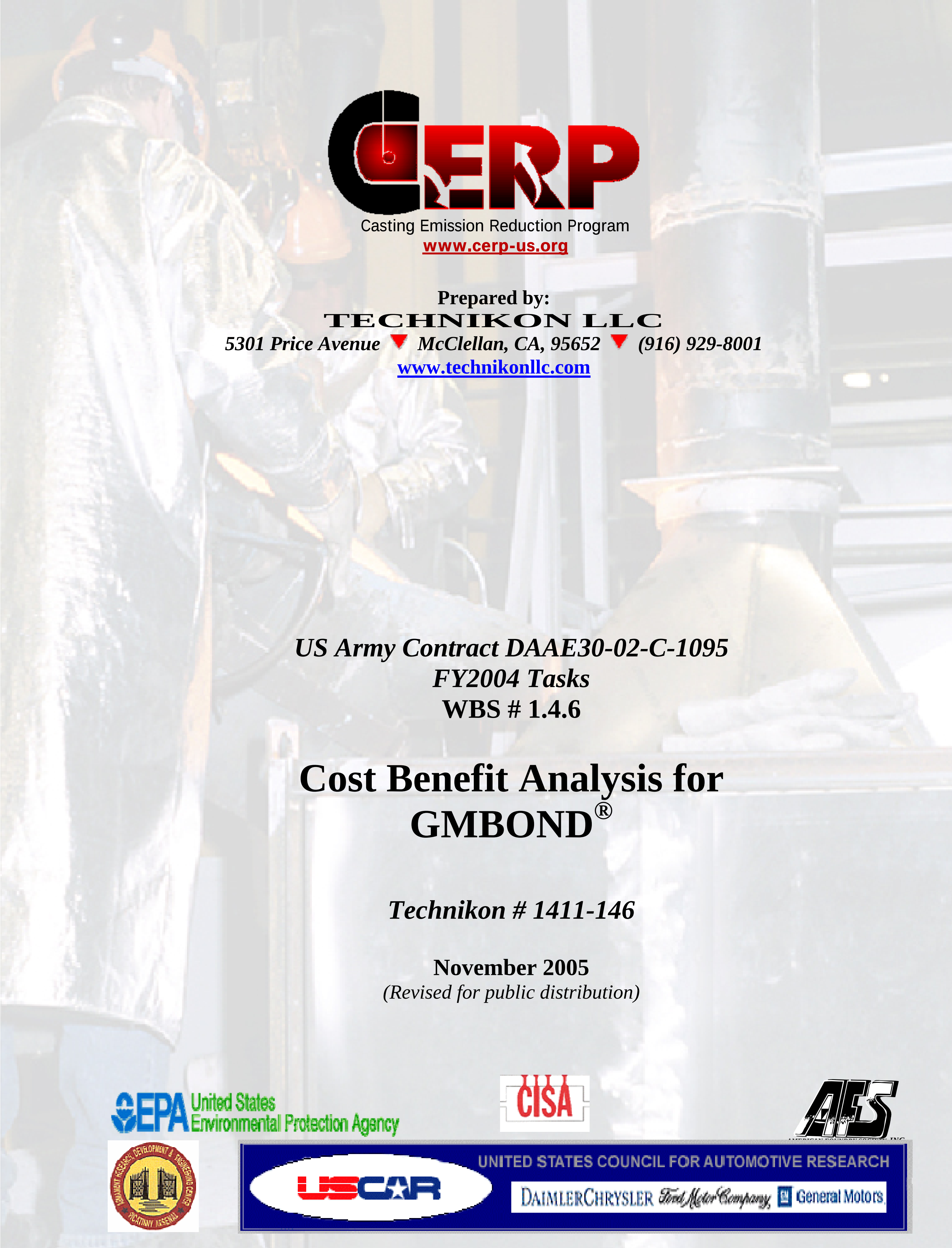

Casting Emission Reduction Program

www.cerp-us.org

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Cost Benefit Analysis for GMBOND®

Technikon # 1411-146

November 2005

(Revised for public distribution)

United States Environmental Protection Agency

UNITED STATES COUNCIL FOR AUTOMOTIVE RESEARCH

DaimlerChrysler Ford Motor Company General Motors

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Cost Benefit Analysis for GMBond®

Technikon # 1411-146

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

Facilities Engineer	*// Original Signed //* Miles Johnson	Date
V.P. Operations	*// Original Signed //* George Crandell	Date
President	*// Original Signed //* William Walden	Date

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Executive Summary

This Technical Report covers testing for the GMBond® machine and process. The Report provides background information, process information, performance and cost comparison of GMBond® and phenolic urethane binder. A new generation V8 engine block (GEN IV block) casting from General Motors (GM) that will go into full production in 2006 was used as a test part for this study. The GEN IV block is being produced using a precision sand process with phenolic urethane binder as the binder for the sand. CERP purchased and installed at a GM foundry, a two-station core blower specifically designed to optimize the GMBond® binder system. Additionally, tooling was purchased to allow the GMBond® machine to make the GEN IV block cover core. This core provides the opportunity to make a direct comparison of phenolic urethane binder and GMBond® core costs and benefits.

Testing and comparing the GMBond® and phenolic urethane binder processes resulted in several conclusions for the General Motors GEN IV cover core concerning performance effectiveness, environmental and cost benefits:

1. **Performance Efficiency**: Several categories were identified in which GMBond® has an advantage over phenolic urethane binder. These categories are improved recycling of scrap core, increased core strength, easy shakeout of casting, and improved environmental safety. Testing concluded that the major disadvantage was cycle time for the GMBond® cover core, which was 36% longer than the revised lighter phenolic-urethane binder cover core.

2. **Capital Costs:** Based on reduced production rates of the GMBond process as compared to the phenolic urethane process, added equipment would be required to support the 500,000 blocks per year requirement. This calculates to approximately $2,400,000 in equipment and $1,080,000 in added core boxes.

3. **Environmental Benefits**: GMBond® is environmentally safe because it has minimal emissions, it has no acid demand value, no ventilation or scrubber equipment is required, and the binder is water-soluble.

4. **Material Cost Comparison**: For this study, a production level of 500,000 core units was used in calculating the cost benefit of GMBond® versus phenolic urethane binder. Cur-

rently, the cover core is the only tooling available for GMBond®. Therefore, the calculation is based on a comparison of costs for the cover core only. Calculations indicate that the annual material disposal cost for GMBond® is $5,606,250 vs. phenolic urethane binder at $6,652,750. The GMBond® process would cost $1,046,500 less per year for material disposal than the existing phenolic urethane binder process for this core.

5. **Energy Costs**: Energy costs were not calculated since equipment use data were unavailable. It is expected that the energy costs for GMBond® would be higher due to longer cycle times and the addition of air drying, vacuum and chiller equipment.

Conclusion: The cover core selected for this test was the largest and most difficult core in the GEN IV precision mold package. The philosophy of selecting this core was based on the concept that if this core could be made competitively, any core in the package could be made. Because of the selection, the data collected only reflects parameters that were achieved with this large cover core. A smaller geometry core might have completely different results, because the cycle time of the process is controlled by the section thickness being heated and cured.

Results of this testing has shown that the cycle time for the cover core is 36% longer in GMBond® vs. phenolic urethane binder. Additionally, the material cost comparison indicated that, for this core, GMBond® is 19% less expensive than phenolic-urethane binder. The savings is generated by the ability to recycle GMBond® sand easily versus having to landfill phenolic urethane binder scrapped and used cores.

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), established in 1994. CERP is a cooperative initiative between the Department of Defense (US Army) and the United States Council for Automotive Research (USCAR). The parties to the CERP Cooperative Research and Development Agreement (CRADA) include The Environmental Research Consortium (ERC), a Michigan partnership of DaimlerChrysler Corporation, Ford Motor Company, and General Motors Corporation; the U.S. Army Research, Development, and Engineering Command (RDECOM-ARDEC); the American Foundry Society (AFS); and the Casting Industry Suppliers Association (CISA). The US Environmental Protection Agency (US EPA) and the California Air Resources Board (CARB) also have been participants in the CERP program and rely on CERP published reports for regulatory compliance data.

1.2. Objectives

The primary objective of CERP is to evaluate materials, equipment, and processes used in the production of metal castings. Technikon's facility is designed to evaluate alternate materials and production processes designed to achieve significant air emission reductions. The facility's principal testing arena is designed to measure airborne emissions from individually poured molds. This testing arena facilitates the repeatable collection and evaluation of airborne emissions and associated process data.

The Technikon foundry is located at McClellan Park, formerly known as McClellan Air Force Base, in the Sacramento Area in Northern California. The information and research data generated are shared with industry, helping to secure American jobs and our national industrial infrastructure.

This program has dedicated an enormous amount of time and effort in testing and developing new casting processes. A major effort has been the testing of new core processes. A core process that demonstrated great promise, but was not fully developed, is the GMBond® process.

1.3. GMBond® Background

General Motors (GM) Research and Development (R&D) began working on finding a new environmentally friendly sand binder system (GMBond®) in the early 1990's. During the same period, GM Powertrain analyzed the lost foam process for the production of future engine castings. The initial GM sand binder R&D team formally presented the technology to the American Foundry Society Casting Congress. This binder was introduced to the U.S. metal casting industry in 1994.

But in 1994, J. Michael Williams, head of GM Powertrain Manufacturing announced, "lost foam will be the aluminum engine block and head process of choice" (Modern Casting, Aug. 2000, page 31 "A History in Foam"). Although there were obvious merits to the new GMBond® sand binder technology, GM Powertrain management had already made a decision to optimize the lost foam process. They realized that, despite the Powertrain commitment to lost foam, their suppliers would have a need for this new (GMBond®) technology because of shakeout and environmental issues related to the phenolic urethane binder process.

GM conducted several validation trials between 1996 and 1999 with Teksid SpA, a large automotive casting supplier, and internally at GM Casting Development Center. Castings were made in green sand molds, with GMBond® cores for cast iron ventilated brake rotors. Aluminum squeeze cast V6 engine blocks were produced in GMBond® in an effort to determine dimensional and shakeout tendencies. Many green sand molded aluminum cylinder heads were produced with GMBond® cores. Teksid and GM verified the shakeout of the process with a semi-permanent-mold aluminum suspension arm. In every case, the casting quality, surface finish, and shakeout were as good as or better than the phenolic urethane binder process. Despite this, GM was not in position to commercialize and optimize this technology for the foundry industry.

Because of its close relationship from past development work, Hormel Foods entered into an agreement with GM in December 1999. This agreement allowed Hormel to commercialize and develop the new technology. As Hormel was introducing this new technology, they were improving and refining the core making process.

In August of 2000, CERP conducted air emissions testing on GMBond® and found that GMBond® produced significantly lower toxic air emissions than all other binders tested. Table 1-1 and Figure 1-1 compare GMBond® with an SO_2 cured acrylic epoxy binder, and phenolic urethane binder. A triethylamine (TEA) cured testing was done on a precision core package for pouring, cooling and shakeout emissions when poured with aluminum.

The US Army (CERP Manager) and the CERP Steering Committee agreed to direct CERP funding to purchase and install a machine designed specifically for the GMBond® process at an operating foundry because of previous positive research results. These positive results included GM production tests, CERP environmental testing and a potential to recycle sand.

This partnership between the private sector and CERP is specifically designed to aid the competitiveness of the US foundry industry. A successful demonstration of the new process at an active foundry would give the process a positive result in meeting the CERP objectives of complying with environmental regulations and maintaining casting quality and global competitiveness. Active sup-

Table 1-1 Comparison Summary Average Results – Pouring/Cooling/Shakeout

Analytes	Acrylic Epoxy (Lb/Tn Metal)	Phenolic Urethane (Lb/Tn Metal	GMBond® (Lb/Tn Metal)
TGOC as Propane	6.23	11.3	1.21
HC as Hexane	6.47	13.4	0.308
Sum of VOCs	2.71	2.46	0.172
Sum of HAPs	1.58	2.02	0.154
Sum of POMs	0.028	0.119	<0.001
TNC as Aniline	NA	NA	0.459
Individual Organic HAPS			
Phenol	0.93	1.62	0.035
Cumene	0.425	NT	<0.001
Toluene	0.042	0.026	0.07
Ethylbenzene	0.037	0.003	0.005
o.m.p-Cresols	0.025	NT	0.017
Benzene	0.025	0.023	0.004
Methylnaphthalenes	0.024	NT	<0.001
o.m.p-Xylenes	0.014	0.029	0.004
Acetaldehyde	0.01	0.036	0.006
Styrene	0.009	NT	0.004
Naphthalene	0.004	0.119	<0.001
2-Butanone	<0.001	0.006	0.004
Aniline	NT	0.156	<0.001
Hexane	I	NT	0.005
Other VOCs			
a-Methylstyrene	1.01	NT	<0.001
Trimethylbenzenes	0.045	0.392	<0.001
Ethyltoluenes	0.027	NT	<0.001
Dimethylphenols	0.009	NT	<0.001
Butyraldehyde/Methacrotein	0.004	0.044	0.002
Octane	<0.001	0.004	0.007
Other Analytes			
Condensibles	2.45	4.07	1.47
1,6-Hexanediol Diacrylate	<0.001	NT	NT
Trimethylol Propane Triacrylate	<0.001	NT	NT
Methane	NT	NT	0.037
Carbon Dioxide	NT	NT	22.3
Methane (Blank)	NT	NT	0.038
Carbon Dioxide (Blank)	NT	NT	22.3

I: Data rejected based on data validation considerations.
NT: Not Tested.
All **“Other Analyses”** are not included in the Sum of VOCs or HAPs.
Individual results constitute >95% of mass of all detected VOCs.
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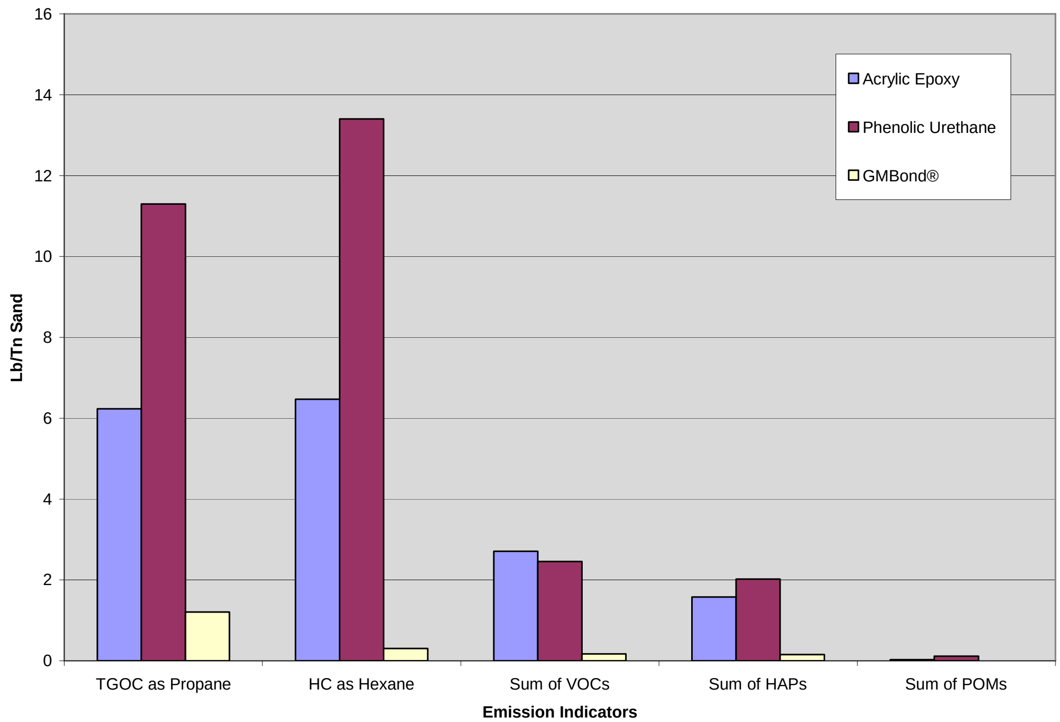
Figure 1-1 Comparison of Emission Indicators– Pouring/Cooling/Shakeout



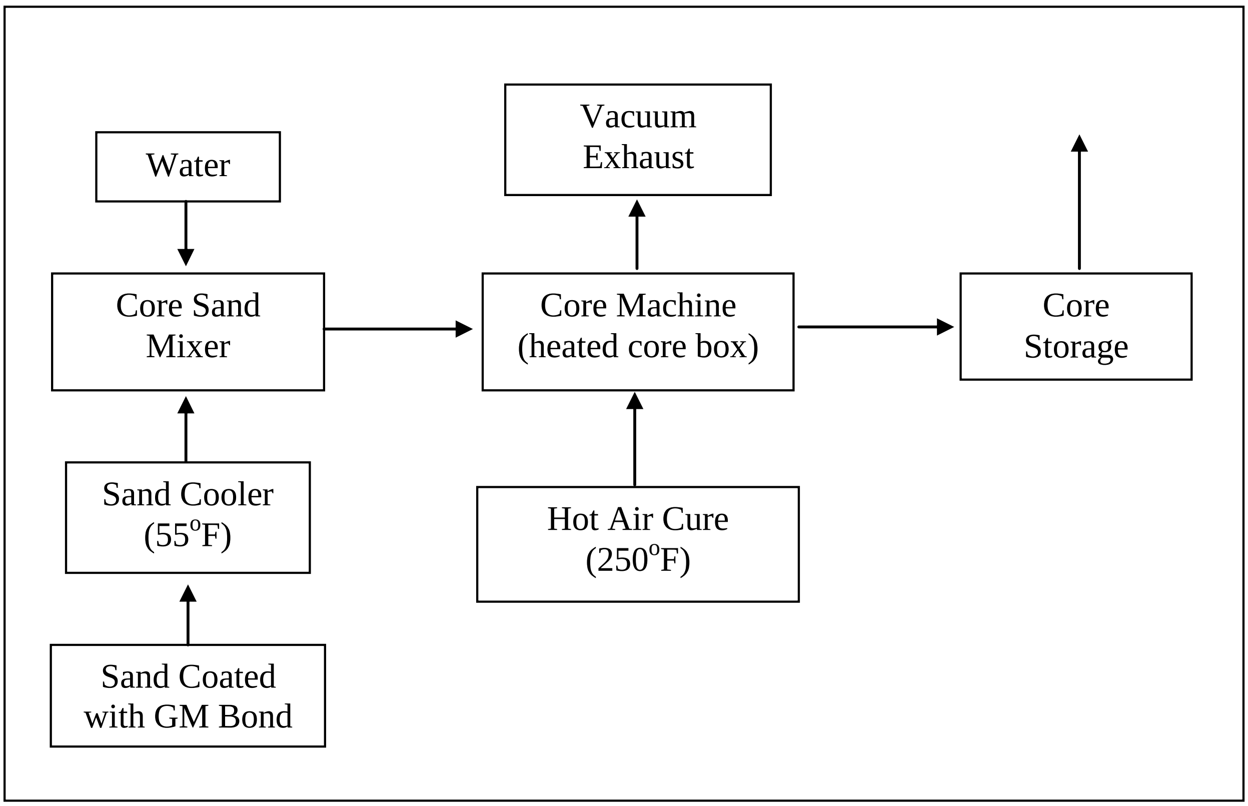
port and cooperation of General Motors, CERP, Hormel, and the United Auto Workers were instrumental in obtaining the necessary approval and funding for a Department of Defense project to demonstrate the viability of the GMBond® process. This resulted in a machine being installed at the General Motors Saginaw Malleable Iron (SMI) operations in Saginaw, Michigan.

The first dual-station, production-type, core-shooting machine developed exclusively for use with the GMBond® process began installation at the General Motors Saginaw Malleable Iron operations on August 20, 2003. The first core produced from this machine occurred on February 17, 2004. This unique machine is designed to accommodate all the core boxes required for the core package of the General Motors GEN IV engine block. This aluminum engine block is manufactured with the precision sand casting process using the phenolic urethane process. This provides a unique opportunity to compare the costs and benefits of the existing phenolic urethane binder with the proposed GMBond® binder. The largest and most challenging core from the General Motors GEN IV core package was selected for testing.

2.0 PROCESS COMPARISON AND GMBOND® VS. PHENOLIC URETHANE BINDER

This section discusses the processes of GMBond® and required equipment needed to operate the process (Figure 2-1) and the testing equipment required for an evaluation. Phenolic urethane binder making process and its parameters are also explained.

Figure 2-1 GM Bond Equipment Layout



2.1. GMBond® Sand Binder Process

Studies in the past few years have shown that GMBond® demonstrates several superior characteristics. Goals of the past GM research were to develop a binder that has numerous features: reduced HAPS and toxic gases, environmentally safe, repeatable recyclability, core strength comparable to current processes, good shelf life, reduced emissions, and easy shakeout from castings. GMBond® Sand Binder consists mostly of animal-derived biopolymers that are combinations of amino acids linked together to form long chains called proteins. The binder is a dry, fine, tan, water-soluble powder. During the initial development, the amount of binder used to make a batch was 1% of the sand's weight. In order to make the binder become adhesive, water (2% of the sand weight) is required. Once water is added to the mixture, it has to be kept at 55°F +/- 5°F. Bonding is accomplished by dehydrating the wet core sand mixture. Biopolymers form covalent bonds as the water is removed from the core to form a crystalline structure. In this process, scrap cores can easily be reused because no chemical reaction has taken place. They just need to be broken down into fine grains again and put back into the system, requiring no extra binder.

Previous work indicates GMBond® sand binder is easy to use, allows for complex core design, and is simple to clean up. Cores made with GMBond® exhibit high strength and surface finish, and when properly cured, are easy to handle right out of the core box (Figure 2-2). In addition, because acid demand value does not affect overall core strength, GMBond® can be used with any type of sand.

Another benefit of using this binder is that water can be used to clean the core box because of the binder's water solubility. Material can simply be wiped away using a cloth. GMBond® dramatically reduces shakeout problems, solid waste, and scrubber costs associated with current commercial binder systems.

Figure 2-2 GEN IV Cover Core

The GMBond® equipment at Saginaw Malleable Iron (SMI) foundry currently has tooling to produce the cover core for the GEN IV V-8 engine blocks. This core is the largest in the GEN IV core package that makes up the complete mold for the casting. This core weighs approximately 230 pounds. The metal being poured is aluminum.

The sand system contains the different elements required to prepare the GMBond® coated sand and transport the sand to the core machine. The process begins with coated sand entering from a storage hopper located directly above the mixer. This bin is designed to provide enough sand for approximately thirty minutes of production. It will hold the equivalent of three (3) tons of sand.

2.1.1. Storage Bin and Hoist

The bags of sand are picked up by the hoist and placed over the bin. They are set on a knife-edge located inside the hopper that rips the bag open allowing the sand to drop into the bin.

When the pre-coated sand is required for production, it is introduced into the chiller and then mixed with a measured amount of water. This equipment cools and hydrates the sand to its optimal operating condition. From the chiller, the sand travels into the mixer. The amount of sand required for each cycle was determined by the specific tooling. The GMBond® project only has the tooling for the cover core. When the sand enters the mixer, water (2% of the sand weight) is added. After water is added to the mixture of sand and binder, the temperature must be maintained at approximately 55°F. The mixing bowl has a water jacket that circulates water to cool the sand. The mixer disperses the water evenly through the sand thus increasing the sand's flowability.

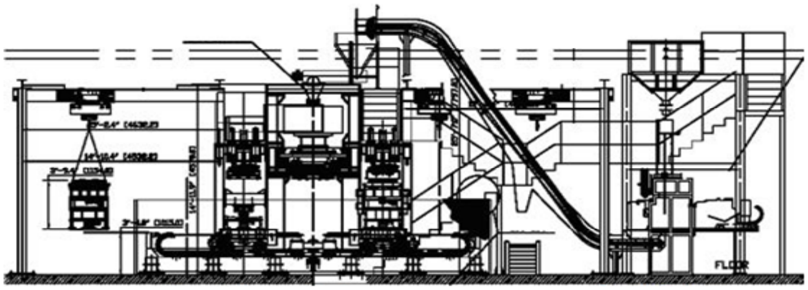
Figure 2-3 Enclosed Belt Conveyor

Due to the limited operating space above the machine, the prepared sand is transported via an enclosed belt conveyor (Figure 2-3). This specially designed conveyor maintains the sand temperature via cool air from the chiller while it is transported into the receiving hopper elevated above the shooting head loading station. This belt is equipped with a cleaning station to ensure that any sand remaining on the conveyor belt is removed for reuse. Like the sand mixer, the receiving hopper needs to be maintained at 55°F. This is accomplished by a water jacket circulating water from the chilled-water system.

2.1.2. Core Machine

The core-shooting machine consists of the receiving hopper located above the shooting head of the machine, one core shooting station, two purging stations, and one core removal station. The receiving hopper stores the sand until it is ready for production. The receiving hopper acts as a preload station for the shooting head and facilitates the removal of any unused sand by discharging it into a sand-receiving flask. It is designed to allow for core unloading and core shooting taking place while a second core is in the air purge, or curing station. This allows for cycle time optimization consistent with customer demand (Figure 2-4).

Figure 2-4 Core Machine and Mixer Layout



2.1.3. Aging Hopper and Screw Conveyor

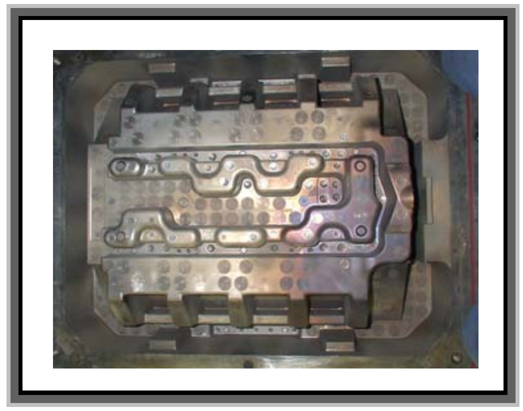
The shooting head moves transversely underneath the receiving hopper to receive a fixed amount of sand necessary for core production. Immediately before entering the shooting head, the sand is augured from the conditioning hopper. Both the aging hopper and screw conveyor are insulated to insure the temperature stays at approximately 55°F (Figure 2-5). The shooting head is uniquely designed in that the sand is shot into the mold cavity. This is accomplished by forcing a metered amount of sand into the cavity via air pressure applied behind the sand column. This process reduces the total amount of air introduced into the cavity resulting in a more uniformly dense sand core.

Figure 2-5 Aging Sand Hopper above Core Machine

2.1.4. Core Box

The core box produces the specific shape of the individual cores. Two flasks make up every pattern: cope and drag. When connected together by clamps or pressure, they make up the pattern for the core (Figure 2-6). For the GMBond® Core Machine, the core box is heated electrically. This is called a "warm box." The box will reach temperatures ranging from 200-300°F.

Figure 2-6 Core Box (Drag Half)



Once the cavity of the mold is completely filled, the core box is sent to the purging station. At this station, the sand core is purged of moisture by the convection of warm air. Warm air that is injected into the core comes from two high-powered air dryers. Air attains an approximate temperature of 250°F.

2.1.5. Air Dryers

The machine and the core box are designed to facilitate air purging in different zones, either independently or simultaneously. This machine has been designed to allow the necessary flexibility to optimize the process by varying parameters until minimum cycle time and material use are established (Figure 2-7).

Figure 2-7 Air Dryers

After purging, the cured core is transferred via the cope to a core unloading station where an operator deposits it onto a pallet for unloading. The operator uses a lifting mechanism to pick up the core and place it into storage (Figure 2-8). Later, the cope half is re-attached to the drag half of the core box.

Figure 2-8 Cover Core Lifting Mechanism

2.1.6. GMBond® Additional Equipment

The commercial development of the GMBond® system required equipment not normally used with the phenolic urethane binder process. This additional equipment was evaluated during the initial phase to allow future specification of the optimum system. A chiller system, vacuum system, and sand coating components are unique to the GMBond® process. Processes for the equipment are explained in the following subsections.

2.1.6.1. *Chiller System*

The chiller system is essential in the GMBond® core making process. Once the water is added to the sand and binder mixture, the mixed sand needs to be kept at approximately 55°F. This system supplies chilled water to the sand mixer, transporting conveyor, and to the receiving hopper. Areas that are not cooled with the chilled water are insulated to keep the sand at its operating temperature.

2.1.6.2. *Vacuum Assist System*

Hormel provided equipment to produce a vacuum assist system (Figure 2-9). This equipment was piped to the purge station on the machine. The vacuum assisted the core drying process by helping draw the moisture from the system. The benefits of vacuum for drying are well documented in the food industry. However, there are considerably less data on the benefit in core manufacturing. Testing indicated that vacuum assist during core manufacturing had little effect. Testing showed that it could be effective as a post cure (out of the core blower) drying process.

Figure 2-9 Hormel Vacuum Assist System

2.1.6.3. *Sand Coating*

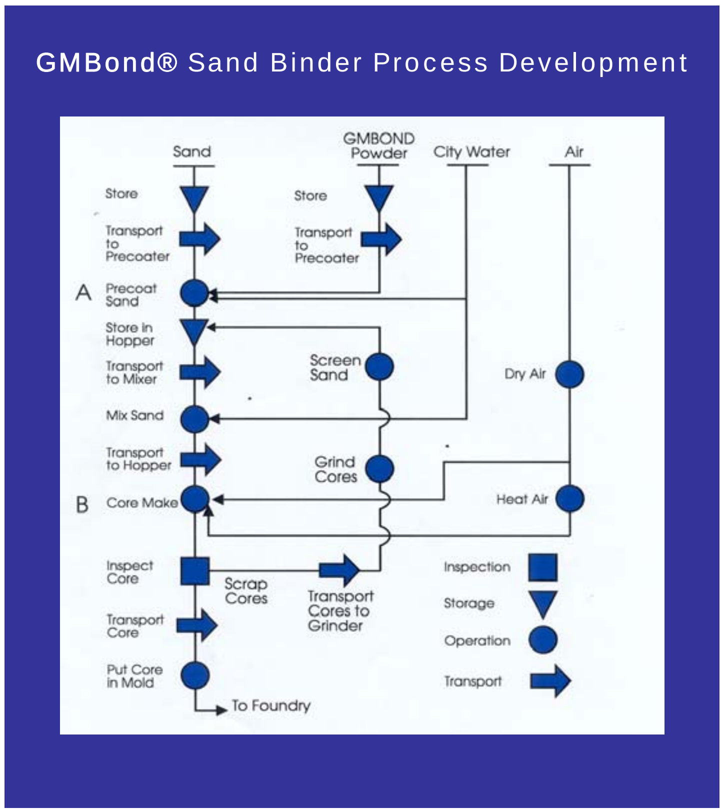
Hormel Foods Corporation produces the sand binder that is used in the

GMBond® core process. It is manufactured in two ways: pre-coated sand or just-in-time mixing. Pre-coated sand is provided with the binder already mixed as a percentage of the sand weight. Just-in-time mixing is the more typical system where the binder is by itself, not mixed with sand. The company receiving the binder then has to have machinery that will correctly mix the binder with the correct sand quantity. The just-in-time mixing was removed and it was decided to receive pre-coated sand, in bags (Figure 2-10). These bags weigh between 2,900-3,000 pounds. Figure 2-11 illustrates the process of pre-coating and use of GMBond® sand in core making.

Figure 2-10 Coated GMBond® Sand Bags

One of the goals was to determine the binder formulation and the most efficient percentage of binder use to produce properties as good as or better than the phenolic urethane binder and for a lower cost and greater environmental benefit.

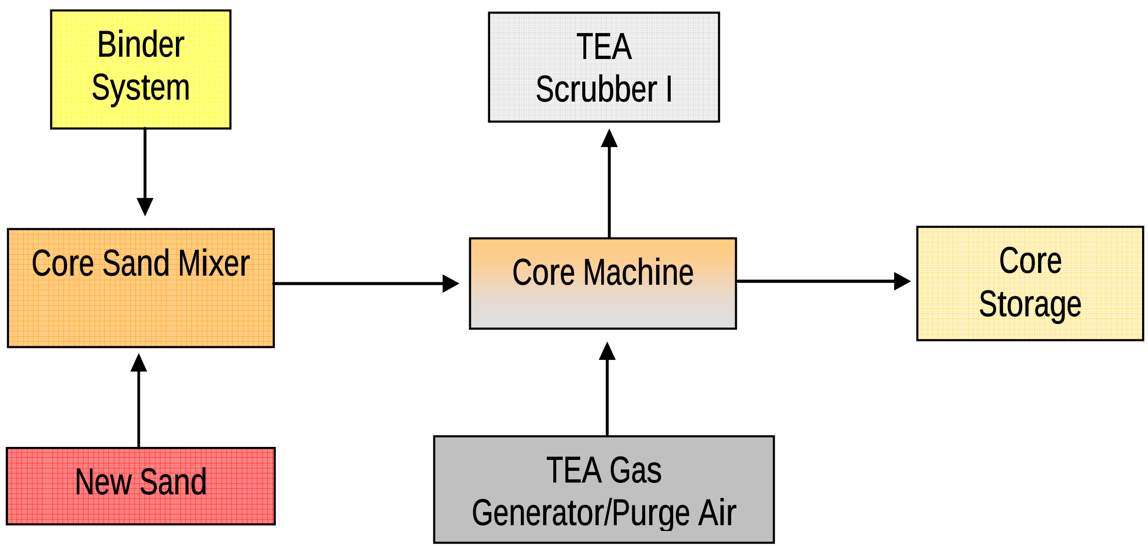
Figure 2-11 Pre-Coated Sand Method Preparation Flow Chart



2.2. Phenolic Urethane Binder Making Process

The current core making process at Saginaw Metal Casting Operations (SMCO) is called phenolic urethane binder. This is the process against which GM-BOND® process is being compared. Both processes are used for what is called Precision Sand, which means the entire mold package is made up of cores instead of the combination of cores set in green sand molds. The phenolic urethane binder process has the tooling for all of the cores in the V-8 engine block core package. A cover core that is produced at SMCO will be the focus of this section. This section discusses the binder, sand and machine parameters, as well as the process that is currently being used for the GEN IV phenolic urethane binder equipment (Figure 2-12).

Figure 2-12 Cold Box Equipment Layout



2.2.1. The Binder

In the phenolic urethane binder process, the binder is a resin that consists of two liquid parts. The two liquids are labeled Part I and Part II. Like the GMBond® process, this binder is currently being used at 1% of the sand's weight. To make up that one percent, the ratio of Part I to Part II is 55/45 for every batch. This binder is mixed with the sand just before the core making. Once mixed with sand, it must be made into a core within approximately 3 hours (depending on the humidity) or the binder characteristics diminish and quality is reduced. This is very different from the GMBond® process where the binder is present in the sand for an indefinite period until water is added.

One benefit of the phenolic urethane binder is that it is not dependent on the sand being held to a cool temperature (55^{o}F) as in the GMBond® process. Since this is the case, a chiller system is not required.

2.2.2. Process

The process of the phenolic urethane binder Core Machine is very similar to the GMBond® Core Machine. Sand starts in a storage hopper. From the hopper the sand travels into the mixer where the resin is added. Resin (1% of the sand weight) is then measured into the sand and mixes for 60 seconds. Since water is not a part of the binder system, none is added. From the mixer, the sand travels to the blow hopper where it is ready to be blown into the core box. The core box requires no external energy source to heat it. The final design weight of the production core is approximately 190 pounds. Once the core is fully blown the core box stays in its position and the shooting head rotates to allow the purging head to get into place. GMBond® process purges with hot air, while phenolic urethane binder process purges with triethylamine (TEA) gas. The TEA gas is blown through the core, hardening it to make it usable for production. Once the core is through purging, it is released from the core box similar to the GMBond® process. A lifting device is used to set the cores onto boards for storage.

Unlike the GMBond® process, a chemical reaction takes place once the TEA gas is pushed through the sand. Since a reaction takes place, sand reclamation is very difficult to do. It is very expensive and time consuming. Since this is the case, every scrap core that is produced is thrown away instead of being reused. Sand recycling is one of the benefits of the GMBond® process and dramatically reduces the cost of the sand and binder.

Other factors that are involved with phenolic urethane binder process are toxic emissions and additional ventilation costs. In order to run this machine, ventilation must be present for the operators and their surroundings. This equipment is very expensive and it is time-consuming to obtain the necessary environmental permits for installation. GMBond® process does not require this equipment, thus it reduces the initial cost and potentially eliminates permitting issues.

2.2.3. Machine and Sand Parameters

The machine and sand parameters with data for the phenolic urethane binder core process for the cover core are listed in the table below. Current research and testing of the phenolic urethane binder process has provided these parameters to produce the cover core.

Table 2-1 Machine and Sand Parameter Data

Parameter Name & Data	*Parameter Name & Data*
Batch size: 146 lbs.	Sand temperature: not required
Mix time: 60 seconds	Gas type: TEA gas
Blow time: 6 seconds (total)	Gas quantity per cycle: 90 cubic centimeter (cc)/(0.143 lbs)
Blow pressure: 3 bar (44 psi)	Core weight: 217 lb.
Core box temperature: not required (phenolic urethane binder)	Cycle time: 110 seconds
Purge time: 90 seconds	Core shelf life: 4-6 wks
Purge pressure: 4 bar (59 psi)	Historical Part 1 plus Part 2 cost is $0.75-0.85/lb.
Purge temperature: not required	Gas cost: $0.85 per lb.
% Binder vs. Sand weight: 1%	Mixed sand price/ton: $45-72

3.0 GMBOND® TESTING, PERFORMANCE AND COST COMPARISON

3.1. GMBond® Core Machine

One of the major issues in commercialization of any new core process is the lack of proper testing equipment. It has proved impractical to convert existing core blowers to optimize the production parameters for GMBond®.

As a result, CERP supported the installation of a large dual station (2 cure stations and a single blow station) core blower designed specifically to properly mix, store and cure (dehydrate) GMBond protein binder. The dual station design allowed increased total cycle time per core box, but the downside is that twice the number of core boxes are required The decision was made to install this test machine at the General Motors Saginaw Malleable Iron Works allowed testing of the core on the pre-production line installed for the development of the Precision Mold process. Once the final production equipment was installed, a direct comparison could be made between the phenolic urethane (PU) binder system and the PU core equipment selected. The core box tooling to make the selected core was also purchased to the specifications necessary for GMBond®. The major differences in the tooling included internal electric heaters that could control the temperature in the box by zones, water-cooled blow tubes and special seals to allow a vacuum to be drawn.

The cover core selected for this test was the largest and most difficult core in the GEN IV precision mold package. The philosophy of selecting this core was based on the concept that if this core could be made core competitively, any core in the package could be made. The weight of the core was designed to be 230 lbs. The section thickness varied between 1 inch in the sidewalls to over 6 inches in the top of the core. The challenge was to show that the productivity of a system designed for GMBond® could match performance with the state of the art equipment and binder systems.

Figure 3-1 Core-Shooting Machine

The core equipment was designed and built by FATA Aluminum in Turin, Italy. The GMBond® core machine (Figure 3-1) was designed as two separate components: the sand system and the GMBond® core-shooting machine. This design was necessary due to the overhead space constraints that were presented to FATA by the SMI foundry layout. Both the sand system and the core-shooting machine were designed to function independently to facilitate the myriad of research and development tests required for process optimization.

A general discussion on the performance and cost comparison between GMBond® and phenolic urethane is provided in the following subsections.

3.2. GMBond® Testing and Data Results

Installation of equipment occurred between August 2003 and February 2004 using SMI skilled tradesmen. Actual testing occurred between 17 February and December 2004. Complete analysis testing was accomplished on the cores and the equipment operating parameters. The core tests performed included Loss on Ignition (LOI), core shell thickness versus purge time, tensile testing, and core scratch hardness tests. This section discusses testing objectives and process, schedule, testing equipment required, machine and sand parameters, initial test evaluations, and testing conclusions.

Figure 3-2 Cover Core

Cope Tooling (upper section) and resulting core surface

3.2.1. GMBond Equipment Testing Objectives

Meetings between GM, Hormel and CERP developed the major objectives of testing for the Cover Core (Figure 3-2) and the GMBond equipment. Primary objectives were:

- Determine minimum cycle time to produce core.
- Evaluate dimensional stability.
- Initially evaluate casting quality.
- Evaluate direct reuse of core, both directly crushed cores (core room scrap) and cores crushed after casting.

In order to accomplish these objectives, a schedule was established for testing periods of one week where CERP, Hormel, and Fata would schedule support people to travel to SMI and work along side GM production workers in making cores and testing variables.

3.2.2. Test Schedule

Testing weeks were scheduled from March to December 2004. Testing was set for the weeks of March 29, April 19, May 17, May 24, June 27 and August 23. Bench scale sand reclaim studies were done September through December 2004. Table 3–1 depicts the start dates, test goals and objectives for each week. Testing lasted one week from the start of the test date followed by process and equipment changes and evaluation. Additional lab testing was also done by Hormel Foods (see Appendix A) during this period on reclaim sand properties.

Table 3-1 Test Plans and Objectives

Week	*Tests*	*Test Objectives*
29 March 2004	• Test changes in tooling to reduce vacuum leaks. • Make cores for casting test- castings to be made week of April 5th • Cut cores to evaluate dryness in different parts of the cores - keep broken cores for recycling tests. • Install data recording software.	• Determine minimum cycle time to produce core. • Initially evaluate casting function. • Evaluate direct use of core, directly crushed and cores crushed after casting.
19 April 2004	• Evaluate methods to reduce cycle time – cut cores to evaluate dryness. • Collect cores for recycling tests. • Make cores to evaluate dimensional stability of cores at SMI. • Evaluate core box vacuum leaks with sonic leak detector	• Initially evaluate casting function. • Determine minimum cycle time to produce core. • Evaluate direct use of core, directly crushed and cores crushed after casting.

Week	Tests	Test Objectives
17 May 2004	• Test vacuum equipment changes	• Initially evaluate casting function. • Determine minimum cycle time to produce core. • Evaluate direct use of core, directly crushed and cores crushed after casting. • Initially evaluate casting function.
24 May 2004	• Test reuse of ground cores. • Continue to evaluate methods to reduce cycle time – vacuum and/or additional hot air.	• Determine minimum cycle time to produce core. • Evaluate direct use of core, directly crushed and cores crushed after casting.
27 June 2004	• Continue to evaluate methods to reduce cycle time. • Make cores for casting trials. • Save cores from casting trials for recycle tests. • Send cores to be crushed for recycling tests.	• Determine minimum cycle time to produce core. • Evaluate direct use of core, directly crushed and cores crushed after casting. • Collect energy usage for GMBond® and equipment.
23 August 2004	• Identify Variables to reduce core hardening time.	• Identify and test mechanisms operating in the core hardening process.
September – December 2004	• Bench scale study on the reuse of GMBond® sand after exposure to heat.	• Determine loss of binder strength.

3.2.3. Machine and Sand Parameters

Machine and sand parameters for the GMBond® process were compared with those of the phenolic urethane binder process for the cover core (Table 3-2).

The data in the parameters are variable to insure the production of a quality, competitive core, and to decrease the cycle time as much as possi-

Table 3-2 Machine and Sand Parameters

Parameter Name	Parameter Name
Batch size:	Mix time:
Blow time:	Blow pressure:
Core box temperature:	Purge time:
Purge pressure:	Purge temperature:
% Binder vs. Sand weight:	Sand temperature:
Cycle time:	Core weight:

ble. Each time a parameter was changed, tests were performed on the cores to evaluate how the changes affected the cycle time and the quality.

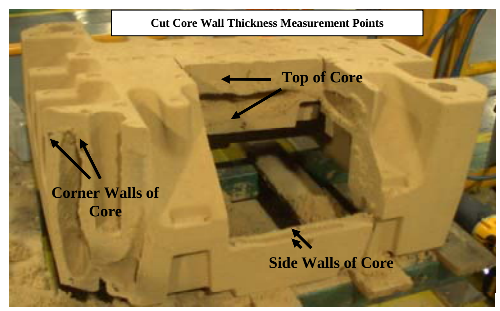
Figure 3-3 LOI Furnace

3.2.4. Testing Equipment

Core tests performed were loss on ignition (LOI), shell thickness versus purge time, tensile-test, core scratch hardness test, and shelf life.

The loss on ignition test determined the percentage of binder that is present on the sand. A sample of sand is taken out of the sand system and taken to the Metallurgy Lab. Fifty grams of the sand-binder mixture is weighed on a scale, and put into a cup. The cup is then put into the furnace where it is heated to approximately 1,800^{o}F (Figure 3-3). The mixture is kept in the furnace for approximately two hours. Once the time is elapsed, the cup is removed from the furnace and set aside until cooled. After the cup is cooled (and can be handled), it is placed on the scale and weighed. The difference between the two weights is the amount of binder that is burned off the sand.

Figure 3-4 Core Wall Thickness Measurement Points

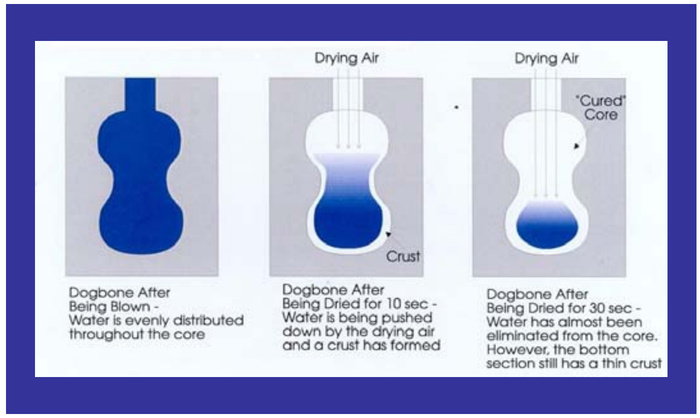


One of the most crucial test parameters on this core is the shell thickness (Figure 3-4), a measure of curing versus purge time. This test determines the overall cycle time. Once the core is out of the machine, it is cut open to determine the thickness of the shell. The shell is the part of the core that is completely dehydrated of water and has the core strength properties.

Figure 3-5 Sand Blower Equipment

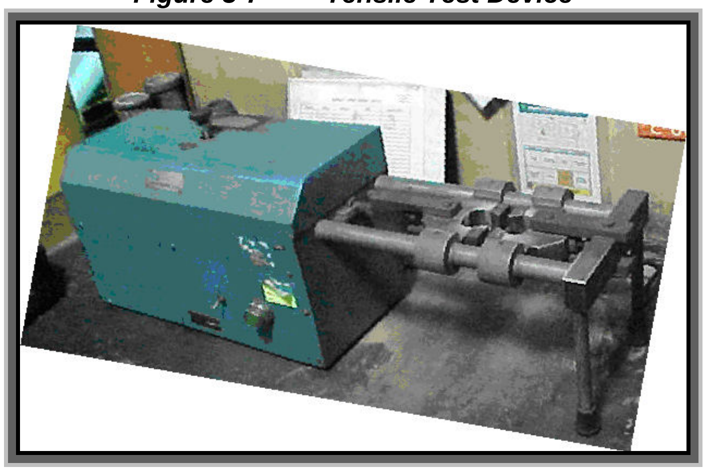
A tensile test is used to determine the strength of the sand-binder mixture. One sample of the sand mixture was taken out of the system and placed into a sand blower device (Figure 3-5). This device blows the sand into a dog bone shape. The sand blower device dehydrates the water from the sand to give it strength (Figure 3-6). Once the cycle time for this machine is completed, the operator takes the dog bone out of the machine. The dog bone is placed into the tensile test device (Figure 3-7) and is pulled horizontally until the core fails. The operator then records the strength from reading of the indicator on top of the equipment.

Figure 3-6 Dog Bond Curing and Testing Process(



A core scratch hardness test was performed on the cores. This determined the strength of the cores outer surface. The equipment used is set on the surface of the core. Next, the gauge is zeroed out. To use the device, the knob on the top of the equipment is rotated one revolution. The gauge then provides a hardness measurement of the core (Figure 3-8).

Figure 3-7 Tensile Test Device



3.2.5. Sand Reuse Tests

Sand reuse testing was done in the SMI sand laboratory to determine the loss of core tensile strength due to reusing scrap cores and heat affected core sand. The test team designed a laboratory test method that would simulate actual production and testing was done at both SMI and Hormel Laboratories. Results of testing are shown as a presentation giving by Hormel at a CERP meeting (see Appendix A).

Figure 3-8 Core Hardness Device

3.2.6. Evaluation of GMBond Performance Parameters

All these tests were compared to similar data for the phenolic urethane binder process on the Gen IV Cover Core being made at another GM Foundry (SMCO). The GMBond® process goal was to equal or surpass the standards set by phenolic urethane binder.

Tests conducted from March to December 2004 allowed the overall objectives to be measured. While not all of the objectives were accomplished, a good understanding of the process was developed. Many modifications to the tooling and the core machine were made because of the testing results in an attempt to optimize the process.

Cycle Time and Curing Testing: With a single set of tooling, the best cycle-time observed for the current cover core is approximately 250 seconds. A cycle time with the machine equipped with two sets of tooling would equate to approximately 150 seconds. The areas that were not cured in the machine would require post curing (external heat or storage of 12+ hours). See Table 3-3 for actual dimensions of core wall thickness at different operating parameters.

Table 3-3 Core Wall Thickness at Different Operating Parameters

Total Purge Time	Tooling Temp Range	Binder Level	Moisture Level	Core Wall Thickness (inches)		
				Top of Core	Side Walls	Corner Walls
300	230-300	1%	2%	1.3	0.4	0.5
400	230-300	1%	2%	1.8	0.5	0.7
250	280-350	1%	2%	1.3	0.4	0.8
250	280-350	0.8%	2%	1.5	0.4	0.6
250	280-350	0.8%	1.8%	1.5	0.4	0.6
300	280-350	1%	2.3%	1.7	0.5	0.7
300	280-350	1%	2%	1.7	0.5	0.7
300	280-350	0.8%	2%	1.9	0.5	0.7
400	280-350	1%	2.3%	2.1	0.7	0.9

<u>Core Sand Recycling:</u> Positive result were obtained with recycling core scrap by crushing and screening the sand allowing the sand to be returned to the sand hopper, therefore recycling all core-room sand scrap. No additional binder was required and the quality of the core that was produced was very close to that of newly coated sand.

Reclaim tests on cover cores from a poured casting were conducted. Cover cores were tested after being removed from the poured permanent mold packages but this testing method proved unreliable because of the lack of control of the process at GM's pilot molding line. A separate test was designed by the test team for heat-exposed sand that measured the loss of strength in rebonding (see Appendix A). Conclusion of testing indicated that 15% to 25% of burnt core sand could be added to new sand making all cores in assembly without major loss of tensile strength. This would eliminate sending the spent sand to landfill, which is the practice with phenolic urethane binder cores being made at GM.

<u>Dimensional Properties:</u> Tests cores for determination of dimensional properties were produced and evaluated by both SMI and the Casting Development and Validation Center's (CDVC) pattern shops. The results were acceptable for the process requirements.

<u>Shakeout Properties:</u> Poured GMBond® cores easily broke down in the shakeout system. Even with the ease of shakeout, the core retained good strength during the pouring operation. Shakeout performance for GMBond® is better than traditional core binder systems.

3.2.7. Performance Parameters Test Conclusions

Since the GMBond® process requires removal of water (dehydration) as the curing process, much of the testing involved optimizing that process. The variables of time, temperature, moisture content, and percent binder level all have an impact on the quality of cores that were produced. The Test teams were able to make the following conclusions for cores with heavy sections such as the cover core.

1. Tests indicate that both conductive heating and convective heating play a role in the curing of the " top" surface of the core while only conductive heating appears to impact the side walls to any degree.

   a. **<u>Curing "Top" of Core:</u>** This area receives significant drying from the airflow through the core as well as the heat migrating from the tooling surface. The top sections cured are over twice as thick as the sections cured on the sidewalls. Reducing the amount of moisture gives a thicker cured section at a given purge time.

b. **Curing Sidewalls of Core:** Data indicate that the heat transfer from the tooling largely controls the curing of the sidewalls. The thickness of the cured sections in the sidewalls does not change significantly with changes in moisture or binder level. Only tooling temperature and purge heating time have an effect.

2. Sidewalls hardened only by heat from the tooling surface limits the cycle time for the cover core because it is the walls that must support the core, when it is sitting on the transfer table or the core machine, and when picked up with the hoist. The overall result is that with the current core geometry, a minimum cycle time of 250 seconds (with only one set of tooling) is required to produce a cured core that will allow handling and removal from the machine.

3. Binder levels of 0.75%, 0.80%, and 1.00% were evaluated with varying moisture levels. For the cover core, the results indicate that a 1.00% binder level with 2.00% moisture level provides the most consistent quality core. If lighter cores are tested, it will be necessary to rerun the binder levels and moisture levels to determine the optimum level for quality and cure time.

4. The use of the vacuum drying chamber after removal of the core from the core machine provided a significant reduction of moisture in the core. After several minutes under vacuum, the core is cured.

5. Cores that have been scrapped prior to pouring can be reused with minor reclaiming and cores that had minor heat exposure can be mechanically reclaimed and reused to make new cores if addition is limited to 15%-25% reclaim sand and 85%-75% new sand.

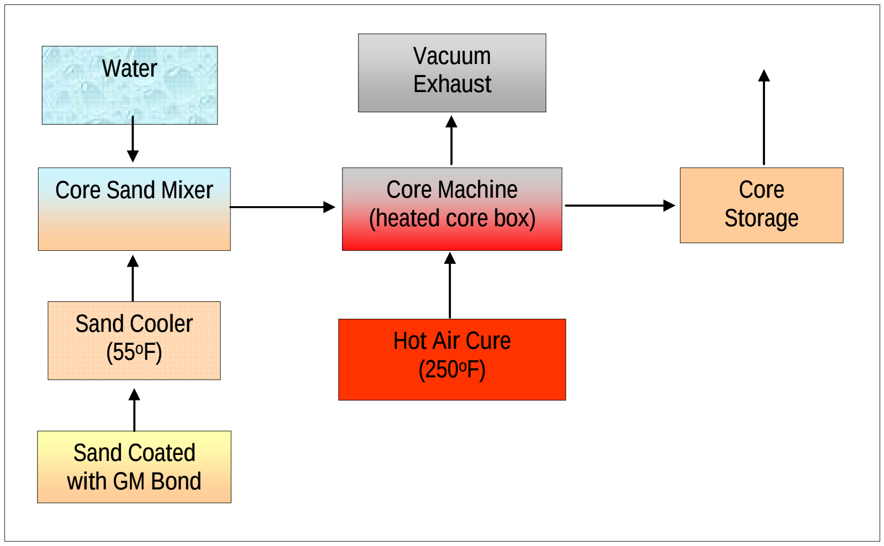
A general discussion on the Performance and Cost Comparison between GMBond® and phenolic urethane binder is provided in the following subsections.

3.2.8. Performance Efficiency

GMBond® productivity, in the core selected, was not as good as phenolic urethane. However, several categories were identified in which GMBond® has an advantage over phenolic urethane binder. These categories are improved recycling of scrap core, reduced toxic emissions and reduced need for ventilation equipment, increased core strength, easy shakeout of casting, good shelf and improved environmental safety.

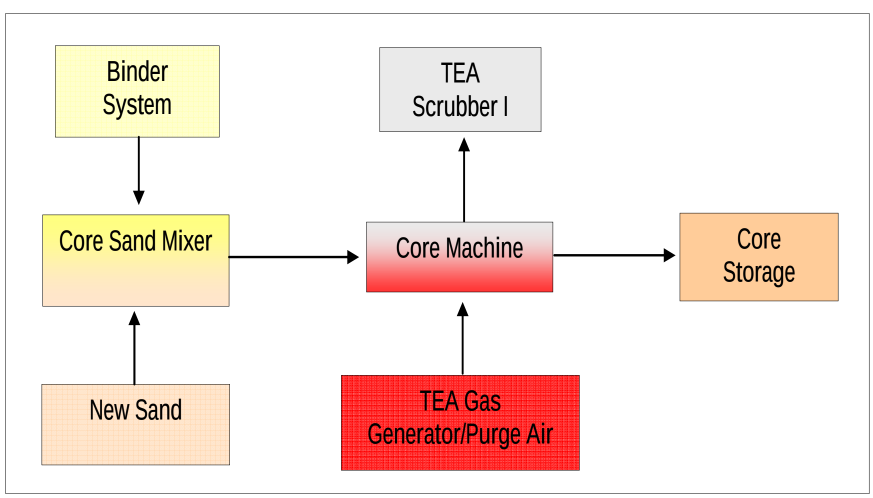
The GMBond® Process (Figure 3-9) purges with hot air. The phenolic urethane binder process (Figure 3-10) purges with triethylamine (TEA) gas. A chemical reaction takes place once the TEA gas is pushed through the sand. Sand reclamation for phenolic urethane is very difficult to accomplish because of the chemical reaction that takes place. Sand reclaiming requires heating the sand to 1300°F and it is very expensive and time consuming. As a result GM elected to landfill every scrap core that is produced. Sand recycling is one of the benefits of the GMBond® process and dramatically reduces the cost of the sand and binder.

Figure 3-9 GM Bond Equipment Layout



GMBond® sand binder is easy to use, allows for complex core design, and is simple to clean up. Cores made with GMBond® exhibit high strength and surface finish and when properly cured and are easy to handle right out of the core box. Since the binder is completely soluble, water can

Figure 3-10 Phenolic Urethane Equipment Layout



be used to clean core boxes and equipment. In addition, acid demand value does not affect overall core strength and GMBond® can be used with any type of sand.

Core machine cycle times for phenolic urethane binder and GMBond® are compared in Table 3-4. The 150-second cycle time for GMBond® cores was achieved assuming the use of 2 core boxes in the dual station core machine. The GMBond® process cycle time was 150 seconds comparing to the rate being achieved at SMCO of 110 seconds or by 36% increase as compared to the phenolic urethane binder process. It can be assumed from this study that a proportional 36% added manpower would be required to produce the cover core at the same rate as the phenolic urethane cores.

Table 3-4 Core Machine Cycle Time Comparison

Process	*Cycle Time Seconds*	*Cores per Hour*
GMBond®	150	24
phenolic urethane binder	110	33

3.2.9. Added Capital Costs

Based on reduced production rates of the GMBond® process as compared to the phenolic urethane process, added equipment would be required to support the 500,000 blocks per year requirement. At the production rate of 33 cores per hour for phenolic urethane cores and a 2-shift operation; figuring in scrap, 5 core blowers would be required. For GMBond® an added 36% more core blowers would be needed. At an approximately $1,200,000 per system this is about $2,400,000 more in equipment for the GMBond® process. Additionally, GMBond® would require 14 core boxes versus the 5 core boxes for phenolic urethane. At approximately $120,000 per core box this amounts to $1,080,000 in tooling expense.

3.2.10. Environmental Benefits

GMBond® is environmentally safe because it has minimal emissions, it has no acid demand value, no ventilation equipment is required, the binder is soluble, water is used to remove the core from the casting, and a cloth is used to wipe away material.

Other advantages of the GMBond® over the phenolic urethane binder process are reduced toxic emissions (see Figure 1-1) and reduced ventilation costs. In order to run the phenolic urethane binder process, ventilation must be present for the operator and the surrounding area. Ventilation equipment air emission permitting is time consuming and expensive. GMBond® process does not require this equipment, thus it reduces the initial cost and saves time.

Another benefit of using this binder is that water can be used to clean the core box because of the binder's water solubility. Material can simply be wiped away using a cloth. GMBond® dramatically reduces the shakeout problems, solid waste, and scrubber costs associated with current commercial binder systems.

3.2.11. Material Cost Comparison

For this study, a production level of 500,000 core units were used in calculating the cost benefit of GMBond® versus phenolic urethane binder based on material costs. Currently, the cover core is the only tooling available for GMBond®. Therefore, the calculation is based on a comparison of costs for the cover core only. GMBond® cores that have been scrapped prior to pouring can be mechanically reclaimed (at $3 per ton) and reused. Phenolic urethane binder cores cannot be reclaimed and therefore are disposed in landfill. GM is running 30% core scrap and this amount of sand was added into the reclaim calculations. GMBond® Cores that had minor heat exposure can be mechanically reclaimed and reused to make new cores if addition is limited to 15% to 25% reclaimed sand and 75% to 85% new sand. For cost estimating purposes 20% reclaimed and 80% new make up sand were used for GMBond®. See Appendix A for study done by Hormel that shows that heated GMBond® sand can be crushed and reused at about 20% additional rate without affecting core tensile strength.

Table 3-5 summarizes the material costs for each process and includes credits for reclaiming GMBond® sand vs. landfilling of phenolic urethane sand. This data shows that over $1 million per year could be saved on the cover core, but this is based mostly on the high scrap rate of this core in phenolic urethane and the fact that all the phenolic urethane sand would be landfilled vs. reused.

Table 3-5 Material Cost Comparison of GMBond® vs. Phenolic Urethane Binder – GM GEN IV Project

	GMBond®			COLDBOX®		
Product	Given	Subtotal	Total	Given	Subtotal	Total
Cores per Year	500,000		500,000	500,000		500,000
Pounds Sand per Casting	230			230		
Basic Sand Usage Tons per Year	57,500		57,500	57,500		57,500
Addition for Scrapped Cores	na		na	17,250		17,250
Total Sand for Binder Usage Tons per Year	80%	57,500	46,000	100%	74,750	74,750
% Sand Reclaimed per Year	20%	57,500	11,500	na	na	na
Binder Cost per Ton, Coated Sand per Year	$65	46,000	$2,990,000	$17	74,750	$1,270,750
Amine TEA Cost per Ton per Year	na	na	na	$17	74,750	$1,270,750
Sand Cost per Ton per Year	$25	46,000	$1,150,000	$25	74,750	$1,868,750
Disposal Tons per Year	80%	57,500	46,000	100%	74,750	74,750
Sand Disposal Cost per Ton per Year	$30	46,000	$1,380,000	$30	74,750	$2,242,500
Reclaim Cost per Ton per Year Including 30% core scrap	$3	28,750	$86,250	na	na	na
TOTAL COST			$5,606,250			$6,652,750

COST DIFFERENCE Per year	
phenolic urethane binder GMBond®	$6,652,750 - $5,606,250 $ 1,046,500

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4.0 CONCLUSIONS

Testing and comparing the GMBond® and phenolic urethane binder processes resulted in several conclusions for the General Motors GEN IV cover core concerning performance effectiveness, environmental and cost benefits. The cover core selected for this test was the largest and most difficult core in the GEN IV precision mold package. The philosophy of selecting this core was based on the concept that if this core could be make competitively, any core in the package could be made competitively.

1. **Core Curing:** Since GMBond® sand requires removal of water as the curing process, the following process parameters ultimately control performance.

    a. **Conductive Heating**: Conductive heating and convective heating play a significant role in the curing of the "top" surface of the cover core; however, only conductive heating affects the sidewalls. Curing "top" of core receives significant drying from the airflow through the core as well as the heat migrating from the tooling surface. The top sections cured are over twice as thick as the sections cured on the sidewalls. Reducing the amount of moisture gives a thicker cured section at a given purge time than would be expected if only the hot air purge was contributing to the drying. Curing the sidewalls of core indicates that it is controlled largely by the heat transfer from the tooling. The thickness of the cured sections in the sidewalls does not change significantly with changes in moisture or binder level. Only tooling temperature and heating time have an effect.

    b. **Sidewalls**: Sidewalls are hardened only by heat, which limits the cycle time for the cover core. The walls must support the core when it is sitting on the transfer table or the core machine or when the core is picked up by the hoist.

    c. **Binder and Moisture Levels**: The cover core results indicate that a 1.00% binder level with 2.00% moisture level provides the most consistent quality core. Binder levels evaluated were 0.75%, 0.80%, and 1.00% with varying moisture levels. A minimum cycle time of 250 seconds (with only one set of tooling) is required to produce a cured core that will allow handling and removal from the machine.

d. **Vacuum Drying**: A significant reduction of moisture in the core was observed when using the vacuum drying chamber after removal of the core from the core machine. After several minutes under the vacuum, the core is completely cured.

2. **Performance Efficiency**: Testing concluded that the cycle time for the GMBond® core was 36% longer than the revised lighter phenolic urethane binder cover core. Several categories were identified in which GMBond® has an advantage over phenolic urethane binder. These categories are improved recycling of scrap core, reduced toxic emissions and reduced need for ventilation equipment, increased core strength, easy shakeout of casting, and improved environmental safety.

3. **Capital Cost:** Based on reduced production rates of the GMBond® process as compared to the phenolic urethane process, added equipment would be required to support the 500,000 blocks per year requirement. This calculates to approximately $2,400,000 in equipment and $1,080,000 in added core boxes

4. **Environmental Benefits**: GMBond® is environmentally safe because it has minimal emissions, it has no acid demand value, no ventilation or scrubber equipment is required, and the binder is water-soluble.

5. **Material Cost Comparison**: For this study, a production level of 500,000 core units was used in calculating the cost benefit of GMBond® versus phenolic urethane binder. Currently, the cover core is the only tooling available for GMBond®. Therefore, the calculation is based on a comparison of costs for the cover core only. Table 3-2 indicates that the annual cost for GMBond® is $5,606,250 vs. phenolic urethane binder $6,652,750. The GMBond® process would cost $1,046,500 less per year than the existing phenolic urethane binder process.

6. **Energy Costs**: Energy costs were not calculated since equipment energy use data were unavailable. It is expected that the energy costs for GMBond® would be higher due to longer cycle times and the addition of air drying, vacuum and chiller equipment.

7. **Results**: This testing has shown that the cycle time for the cover core is 36% longer in GMBond® vs. phenolic urethane binder. Additionally, the material cost comparison indicated that GMBond® is 19% less expensive than phenolic urethane binder. For this core,

the savings is generated by the ability to recycle GMBond® sand easily versus having to land fill phenolic urethane binder scrapped and used cores.

8. **Conclusion:** The cover core selected for this test was the largest and most difficult core in the GEN IV precision mold package. The philosophy of selecting this core was based on the concept that if we could make this core competitively, we could make any core in the package. Because of the selection, the data collected only reflects parameters that were achieved with this large cover core. A smaller geometry core might have completely different results, because the cycle time of the process is controlled by the section thickness being heated and cured.

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APPENDIX A REUSE OF SAND WITH PROTEIN BINDER - BRIEFING SLIDES FROM HORMEL FOODS TESTING

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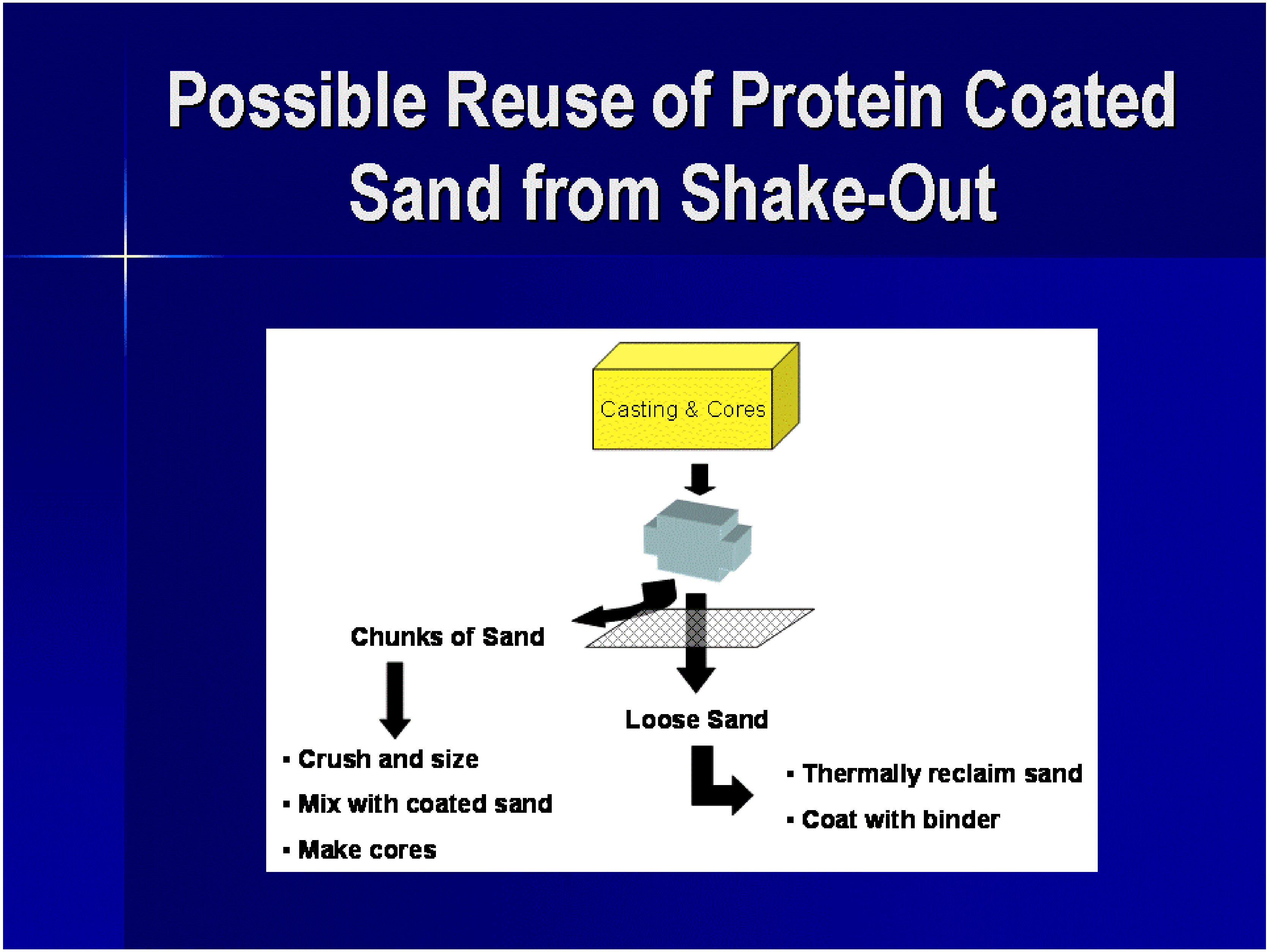
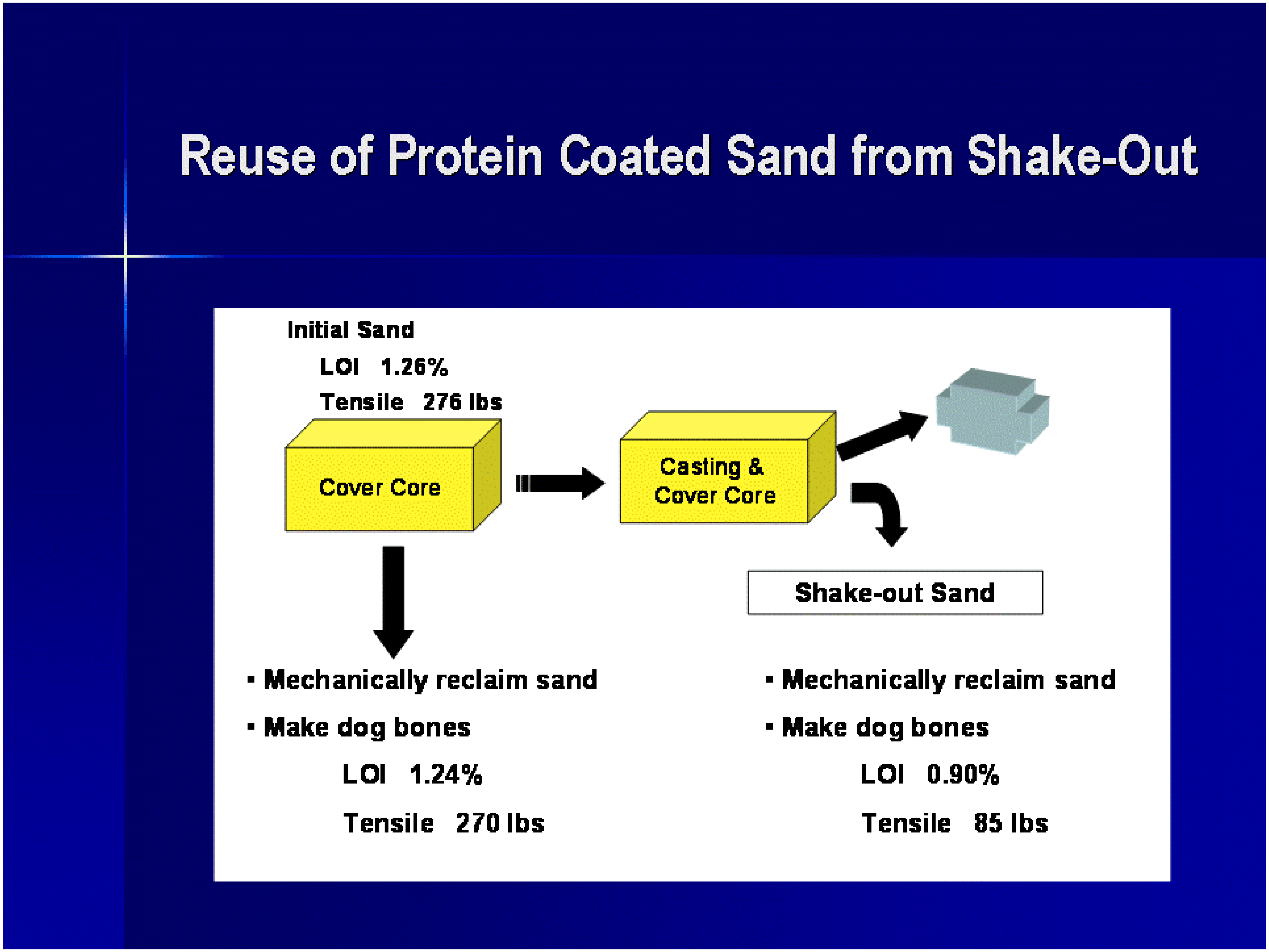
The following briefing was presented by Hormel Foods at the February 2005 CERP meeting. The briefing discusses testing done at Hormel to determine the amount of heat affected GMBond® sand could be reused in a new sand mix without significant loss in tensile strength. The conclusion was that 15% to 25% of the burnt sand could be added to new GMBond® sand.


Possible Reuse of Protein Coated Sand from Shake-Out
Casting & Cores
Chunks of Sand
▪ Crush and size
▪ Mix with coated sand
▪ Make cores
Loose Sand
▪ Thermally reclaim sand
▪ Coat with binder

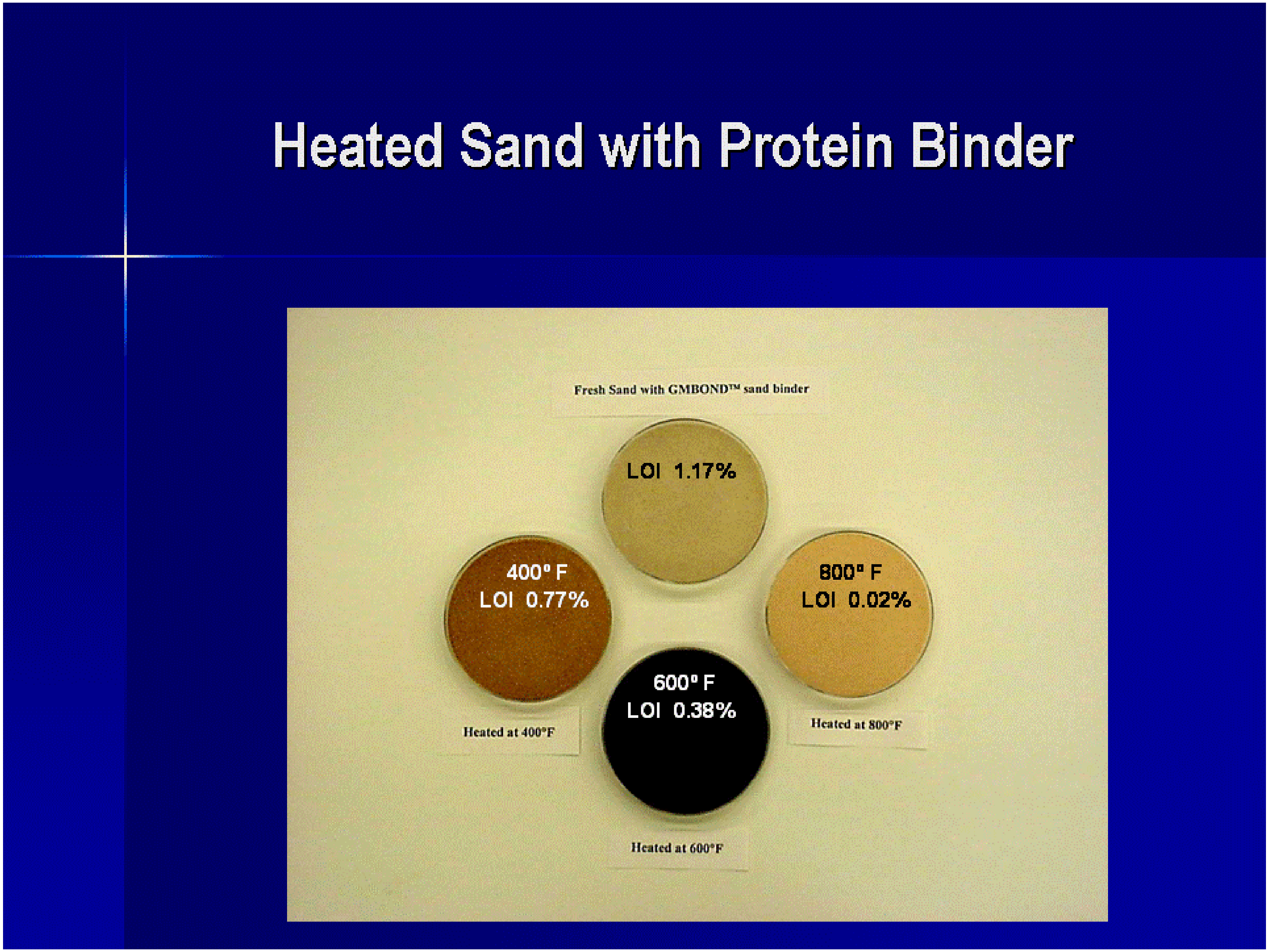
Reuse of Sand with Protein Binder

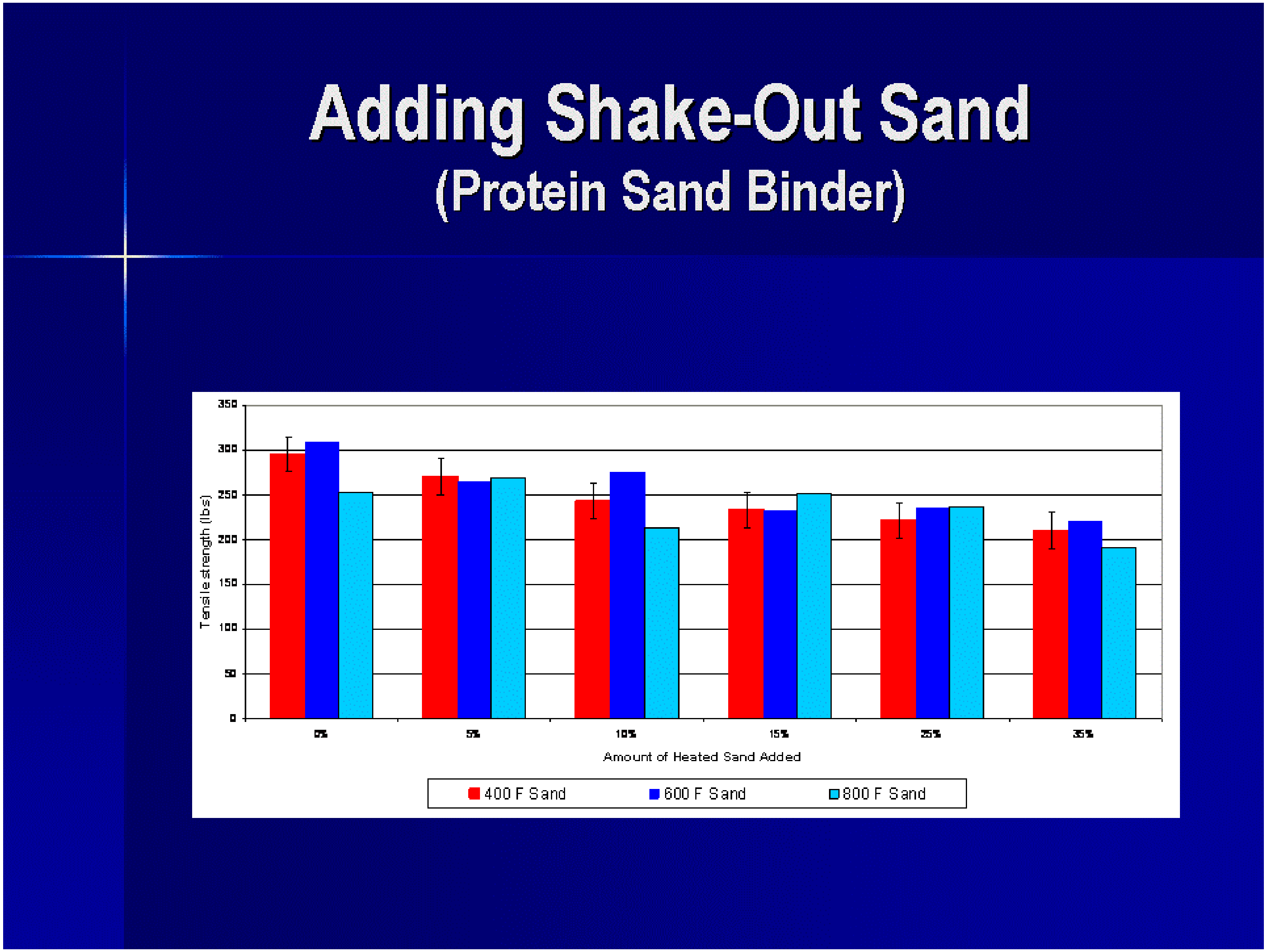
- Tests at GM – Poured Cover Cores Crushed and Tensile Testing Completed
- Lab Tests with Head Damaged Core Sand Completed


Reuse of Protein Coated Sand from Shake-Out
Initial Sand
LOI 1.26%
Tensile 276 lbs
Cover Core
Casting &
Cover Core
Shake-out Sand
▪ Mechanically reclaim sand
▪ Make dog bones
LOI 1.24%
Tensile 270 lbs
▪ Mechanically reclaim sand
▪ Make dog bones
LOI 0.90%
Tensile 85 lbs

Lab Test of Shake-Out Sand Reuse
(Protein Sand Binder)

- Lake Sand Coated with 1% Protein Binder
- Heat 4 Hours at 400, 600 or 800ºF
- Mix at 0% to 35% with Original Coated Sand
- Make 9 Dog Bone Tensile Specimens


Heated Sand with Protein Binder
Fresh Sand with GMBOND™ sand binder
LOI 1.17%
400° F
LOI 0.77%
800° F
LOI 0.02%
600° F
LOI 0.38%
Heated at 400°F
Heated at 800°F
Heated at 600°F


Adding Shake-Out Sand
(Protein Sand Binder)
350
300
250
200
150
100
50
0
Tensile strength (lbs)
0%
5%
10%
15%
25%
35%
Amount of Heated Sand Added
400 F Sand
600 F Sand
800 F Sand

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APPENDIX B ACRONYMS AND ABBREVIATIONS

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Acronyms and Abbreviations

AFS	American Foundry Society
CARB	California Air Resources Board
CBA	Cost Benefit Analysis
CDVC	Casting Development and Validation Center
CERP	Casting Emissions Reduction Program
CRADA	Cooperative Research and Development Agreement
GEN IV	New generation V8 engine block
GM	General Motors
HAP	Hazardous Air Pollutant
LOI	Loss on Ignition
PCS	Pour/Cooling/Shakeout
PUCB	Phenolic Urethane phenolic urethane binder
R & D	Research and Development
TEA	Triethylamine
US EPA	United States Environmental Protection Agency