PREPARATION OF AN APPLICATION FOR APPROVAL TO USE STABILIZED PHOSPHOGYPSUM AS A FILL MATERIAL FOR COASTAL PROTECTION DEVICES

FINAL REPORT

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PREPARATION OF AN APPLICATION FOR APPROVAL TO USE
STABILIZED PHOSPHOGYPSUM AS A FILL MATERIAL
FOR COASTAL PROTECTION DEVICES

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PERSPECTIVE

The need for coastal protection devices has never been demonstrated as well as it was when the Gulf coast was subjected to hurricanes that devastated much of the coastline from Texas to Mississippi. The effect of these storms was added to the routine everyday loss of land mass all along the Gulf coast. Loss of these land/marsh areas has meant that many of the marshes that served as nurseries for marine creatures have been and are still being destroyed. The long-term results of these losses for the fishing industry are still not well defined.

The situation along the Louisiana coast presents conditions that are not found in all of the other Gulf coast states. Much of the Louisiana coastal area soil has a low load-bearing strength and any material that is placed on these soils tends to sink into them and disappear over time. Using very heavy materials like granite and limestone for coastal protective devices requires regular and frequent addition of material in order to maintain the proper functioning of the installed coastal protection devices. The use of phosphogypsum in the manner proposed would provide a lower-weight material that would not need to be replaced as often as the presently used materials. In addition, the cost of building the coastal protection devices would be reduced and whatever monies that were available for this purpose would allow the construction of more coastal protection devices. All of this could be accomplished while using a material that is readily available and well suited for the proposed use.

While it would not be a major consideration, the fact that these briquettes form a calcium carbonate coating over time means that some carbon dioxide is being removed from the atmosphere and with the concerns over global warming, removal of even this amount of carbon dioxide would appear to be of some value.

G. Michael Lloyd, Jr.
Research Director, Chemical Processing
ABSTRACT

This report covers an application prepared to obtain approval from EPA for an alternate use of phosphogypsum (PG) in a “coastal protection device in the form of a mechanically stabilized embankment” consisting of PG briquettes and geotextile fabric with limestone or granite as armoring. The application was prepared in two sections: (1) an embankment with 350 metric tons of raw phosphogypsum on the shoreline of Lake Salvador, Louisiana and; (2) a test structure with 650 kg of PG in Lake Pontchartrain.

The calculated risk for all receptors is well below the EPA’s individual risk criteria of $1 \times 10^{-4}$. The risk values were obtained using a very conservative approach that includes the possibility of a person digging part of the material from under the limestone armor, the geotextile bags and geogrid and consuming it. Also, the use of the embankment and test structure as fishing platforms and as 35% of the annual seafood consumption from the contaminated zone is considered.

The information included with this application provides evidence that the radiological risk associated with the use of PG as a fill material in coastal protection devices represents a lower health risk to public health than the disposal in stacks.
ACKNOWLEDGMENTS

The research team would like to acknowledge Mosaic’s Uncle Sam facility, for providing the laboratory analysis report of samples from the phosphogypsum from their stacks. The team would also like to acknowledge the help of Ms. Sarah Jones on the site selection, data compilation and proofreading. Foremost, we would like to express our sincere appreciation to the Florida Institute of Phosphate Research for its financial support and assistance in this project.
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EXECUTIVE SUMMARY

The proposed small-scale research application of phosphogypsum is considered the next logical step after FIPR project #99-01-162S was completed, and it is part of FIPR project #06-01-197. The goal of #99-01-162S was to find the PG:Class C fly ash:Portland Type II cement combination that minimized fabrication costs and the effective diffusion coefficients for calcium, sulfate and $^{226}\text{Ra}$ to maintain physical integrity under saltwater submergence. This research resulted in four combinations that met all criteria and have the potential for commercialization.

The present report covers an application prepared to obtain approval from EPA for an alternate use of phosphogypsum (PG) in a “coastal protection device in the form of a mechanically stabilized embankment” (hereafter referred to as the embankment) consisting of PG briquettes and geotextile fabric with limestone or granite as armoring. The application was prepared in two sections: (1) an embankment with 350 metric tons of raw phosphogypsum and; (2) a small-scale field study, or test structure, with 650 kg of PG.

A risk analysis and an application for the test structure and for the evaluation of the embankment were prepared and submitted to EPA to obtain approval for an alternate use of PG.

The location of the small-scale test will be in the Orleans Parish, along the south shore of Lake Pontchartrain, adjacent to the University of New Orleans Center for Energy Research and Management. A total of 650 kg of PG is proposed to be used for the small-scale field study and permission to use a total of 900 kg has been requested from the EPA for this purpose to account for the material needed on the test structure, the material needed for testing and the weight loss due to drying of the material. The location of the embankment will be on the shoreline of Lake Salvador, Louisiana. It is anticipated that the embankment application will require approximately 350 metric tons (378 tons) of raw phosphogypsum. The location has been subject of several projects to protect the shoreline from erosion.

The results of the risk analyses provide evidence that the radiological risk associated with the use of PG as a fill material in coastal protection devices represents a lower health risk to the public than its disposal in stacks.

Risk calculations were performed for the embankment and for the test structure. Three categories of receptors were considered for the test structure: briquetting facility personnel, general public and Louisiana State University (LSU) research personnel. The risks to the briquetting facility and LSU personnel for indoor research activities were added to the total risk of these receptors, even though the indoor research activity with the proposed amount of PG (650 kg) is well below the 7,000 lbs. established by EPA and hence does not require previous approval. For the embankment, five categories of receptors were considered: LSU researchers, drivers, construction workers, briquetting
facility workers and the general public. The application included information about the measures to ensure PG will be contained in all phases of the project, including field, laboratory and transportation phases and the final disposition of the material.

The maximum individual risk calculated from the test structure was: (a) $1.1 \times 10^{-6}$ for LSU personnel; (b) $1.5 \times 10^{-8}$ for non-LSU personnel; and (c) $3.4 \times 10^{-7}$ for the general public. For the embankment, the risk calculated was: (a) $1.5 \times 10^{-7}$ for LSU personnel; (b) $2.9 \times 10^{-8}$ for drivers; (c) $6.6 \times 10^{-6}$ for construction workers; (d) $3.5 \times 10^{-6}$ for briquetting personnel; and (e) $6.1 \times 10^{-16}$ for the general public. The calculated risk for all receptors was well below the EPA’s individual risk criteria of $1 \times 10^{-4}$. The risk values were obtained using a very conservative approach that includes the possibility of a person digging part of the material from under the limestone armor, removing it from the geotextile bags and geogrid, and consuming it. The calculations also assumed that a person would use the embankment (and test structure) as a fishing platform, while consuming 35% of his/her annual seafood consumption from the contaminated zone.

The calculated doses due to this project are well below the EPA limits (25 mrem·year$^{-1}$), with a maximum dose of 7.4 mrem·year$^{-1}$ for the construction workers (this assumes no protection was used during the construction).

The application was submitted in January 2009 to EPA. The researchers are in contact with EPA every 3-4 weeks regarding its progress. The application was sent by EPA to an external consultant for review. EPA also sent it to the Louisiana Department of Environmental Quality (LDEQ) for evaluation regarding the permit requirements for the application of phosphogypsum on the Louisiana coast. The researchers are in contact with LDEQ, which is in the process of making a decision about the permitting requirements for this project.
INTRODUCTION

Phosphate fertilizer is produced from phosphate ore that contains naturally occurring radioactive material (NORM), with Ra$^{226}$ being the predominant element of concern. The process that yields phosphoric acid from the ore also creates a solid by-product referred to as phosphogypsum (PG, CaSO$_4$·2H$_2$O) at a phosphoric acid:PG ratio of 1:4.5 to 5.5 (EPA 2009). The Ra$^{226}$ is concentrated in the PG, and this puts it into the category of a technologically enhanced naturally occurring radioactive material (TENORM) (EPA 2007). Since the mid-1980s, the annual production rate of phosphogypsum has been in the range of 44 to 51 million metric tons. The total amount generated in the United States from 1910 to 1981 was about 7.7 billion metric tons (EPA 2009). Central Florida is one of the major phosphoric acid-producing areas, generating about 32 million metric tons of phosphogypsum each year and contributing to the nearly one billion metric tons of phosphogypsum already in stacks (EPA 2009). These stacks create both an economical and an environmental burden on the industry. Subsequently, the industry is seeking a long-term solution for the use of PG for environmentally sound and economically favorable purposes. Various beneficial alternative uses of PG are being sought to decrease risks to humans and the environment, to reduce storage costs, and to create an economic market for PG products.

There are several potential uses for PG, including soil amendments in agriculture, road base construction, vitrification, wallboard and landfill cover (Birky 2002). However, only PG from North Florida has radiation levels low enough (<10 pCi·g$^{-1}$) to qualify for agricultural uses (FIPR 1996). The PG from central Florida has an average Ra$^{226}$ concentration of 26 pCi·g$^{-1}$ (Lloyd 2002). A more economically feasible and environmentally sound alternative is the use of PG briquettes as mechanically stabilized fill material in coastal protection devices (Guo and others 2001, Rusch and others 2001, Deshpande 2003). This application provides one of the best means to minimize human radon gas exposure since the airborne vector of radon transmission is essentially eliminated.

This proposed use of PG briquettes is a very attractive alternative as our nation’s wetlands and beaches are disappearing significantly, resulting in intense restoration efforts in many states. Our nation’s beaches and coastal wetlands serve as transition zones between sea and land and provide a buffer zone against shoreline erosion. Beaches and wetlands are also highly valued as economic and recreational resources. However, coastal beach and wetland erosion is a serious problem in the United States, particularly along the Gulf Coast. Our nation’s wetlands are disappearing at a rate of more than 78 km$^2$·yr$^{-1}$ (LDNR 2009). Nearly half of Florida’s sandy beaches are suffering serious erosion that “threatens substantial development, recreational, cultural, and/or environmental interests” to the coastal communities (FDEP 2009).
LSU RESEARCH

**Initial Stabilization of Phosphogypsum Marine Application Composites and Bioaccumulation Studies**

Since the mid-1990s, LSU researchers have been investigating beneficial uses for phosphogypsum as it relates to marine applications. Initial research using Portland Type I cement as the binding agent resulted in an estimated commercial production cost of $39·ton$^{-1}$ (Chen and others 1995). The bioaccumulation potential and ecological effects from stabilized PG blocks were investigated by Nieland and others (1998), Wilson and others (1998), and Chen and others (1995). Chen and others (1995) investigated the leaching and bioaccumulation of toxic metals and Ra$^{226}$ from 70%:30% PG:Portland Type I cement composites. There was no evidence of leachability and bioaccumulation of toxic metals and Ra$^{226}$. Intact PG composites contained market-size oysters attached to the surface. Many different kinds of marine organisms were found to colonize on the PG composite surface. Nieland and others (1998) investigated the bioaccumulation of the Ra$^{226}$ and toxic metals in an aquatic food chain exposed to PG:Portland Type I cement blocks. Among the analyses of five experiments and six control groups for Ra$^{226}$, copper, zinc, cadmium, lead, chromium and arsenic, the results were equivocal and showed little evidence of bioaccumulation through the food chain. Wilson and others (1998) investigated the effect of PG:Portland Type I cement blocks on the structure of the marine organism community. The experiments were conducted in four 1,000 m$^2$ estuarine ponds. No differences in community structure attributable to the presence of PG could be detected among benthic invertebrates, natant invertebrates, or fishes.

**Optimization of PG Composites: Structural Integrity, Release of Ra$^{226}$ and Constituents of Concern**

Much research has been performed on the stabilized phosphogypsum composite specimens to understand their leaching behavior and determine the diffusivities of calcium and sulfate (Guo and others 1999a, 1999b, 2001), trace metals such as As, Pb, Ba, Cr, Fe, Al and Mn, and radionuclides such as Ra$^{226}$ and Rn$^{222}$ (Gokmen 1995; Fan 1997; Deshpande 2003). Stabilizing PG with Class C fly ash and Portland Type II cement minimizes the migration of Ra$^{226}$ from the PG composite into the surrounding environment and prevents dissolution of the calcium and sulfate (Guo and others 2001, 2003; Deshpande 2003). The most recent research (Deshpande 2003) showed that four combinations (73%:25%:2%, 67%:30%:3%, 63%:35%:2% and 62%:35%:3% PG:Class C fly ash:Portland Type II cement) can survive submersed for more than one year (the project ended and observations were ceased at this point).

Fan (1997) focused on decreasing the Portland Type I cement content from 30% to 15% to reduce the production cost. Fan (1997) also measured the leaching characteristics and structural integrity of the PG:cement blocks. The results indicated high release rates of Ra$^{226}$, As and Pb ions during the first 3 to 4 days of leaching, with a
gradual decline observed thereafter in fresh- and saltwater conditions. The unconfined strength of the blocks met the strength requirements (3447 kPa) when fabricated under a 363 kilogram compaction level. More importantly, Fan’s work illuminated the relationship between block composition and dissolution problems when submerged under saltwater conditions. Even though his effort of reducing production cost failed, his work was the impetus for more recent research (Guo 1998), which defined the proper composite configuration.

During the subsequent years, the LSU research team has shown that composites containing PG, Portland Type II cement, and Class C fly ash exhibit the greatest potential for long-term marine application (Guo 1998, Guo and others 2003, 2004; Deshpande 2003; Rusch and Guo 2003). Several studies have been conducted on the stabilized phosphogypsum composites to understand their leaching behavior and to determine the diffusivities of calcium and sulfate (Guo 1998, Guo and others 2001; Deshpande 2003), trace metals such as As, Pb, Ba, Cr, Fe, Al and Mn (Deshpande 2003) and radionuclides such as Ra\textsuperscript{226} and Rn\textsuperscript{222} (Deshpande 2003).

Guo (1998) showed a mixture consisting of 62%:35%:3% PG:Class C fly ash:Portland Type II cement could survive in natural saltwater conditions for more than two and one-half years. The reasons for the survival of the PG:Class C fly ash:Portland Type II cement composites were identified as minimal ettringite development and a high pH value on the block surface, which induced the precipitation of a CaCO\textsubscript{3} coating onto the block (Figure 1). The CaCO\textsubscript{3} coating prevented the block from dissolving. Guo and others (1999) also investigated the microstructure and determined the diffusion coefficients of PG:Portland Type II cement:lime composites. This research indicated that the development of ruptures contributed to the observed diffusion coefficient increase from $10^{-7}$ to $10^{-5}$-$10^{-4}\text{ cm}^2/\text{day}$. Scanning electron microscopy (SEM) and microprobe results (Guo 1998, Guo and others 2001) showed that the conditions necessary for stabilized PG composites to survive in the saltwater environment were: (1) the stabilized PG composites should have a strong sulfate-resistant surface and (2) the local pH environments on the stabilized PG composites should be above 11. This higher local pH environment will result in the formation of calcium carbonate, which protects the PG composites and reduces the diffusion of toxic metals and radium. For PG:fly ash:cement composites, the stronger calcium carbonate coating embedded with fly ash particles covers the higher sulfate-resistant composite surface and both contribute to the survival of PG:fly ash:cement composites.
Research focused on stabilizing PG with Portland Type II cement and Class C fly ash for use in marine environments was reported in Florida Institute of Phosphate Research (FIPR) publication 01-162-211 (2005) as part of FIPR project 99-01-162S. The 73%:25%:02%, 67%:30%:03%, 63%:35%:02% and 62%:35%:03% PG:Class C fly ash:Portland Type II cement composites demonstrated promising results with no signs of degradation after 12 months of natural saltwater submergence (Rusch and others 2005). The Ra\textsuperscript{226} concentrations in the TCLP leachate were well below the current EPA regulatory value for drinking water (5 pCi L\textsuperscript{-1}). The metal concentrations in the leachate were also well below the EPA toxicity characteristics limits. A one-dimensional diffusion model based on Fick’s second law with a non-zero surface concentration at the solid-solution interface was developed to calculate effective calcium and sulfate diffusion coefficients of composites placed in saltwater. This model determined that the range of effective calcium, sulfate and Ra\textsuperscript{226} diffusion coefficients were $1.36-8.04 \times 10^{-13}$ m\textsuperscript{2} s\textsuperscript{-1}, $2.96-7.20 \times 10^{-13}$ m\textsuperscript{2} s\textsuperscript{-1} and $1.46-2.90 \times 10^{-17}$ m\textsuperscript{2} s\textsuperscript{-1}, respectively (Rusch and others 2005). This model also predicted that calcium, sulfate and Ra\textsuperscript{226} will stop leaching at a critical time ($t_c$) of 64-78, 122-137 and 150-470 days, respectively, when the leaching processes are balanced by precipitation reactions (Rusch and others 2005). The effective diffusion coefficients of Cu, Cr, Zn ranged from $6.46 \times 10^{-12}$ to $1.21 \times 10^{-11}$ m\textsuperscript{2} s\textsuperscript{-1}, $5.83 \times 10^{-13}$ to $1.69 \times 10^{-12}$ m\textsuperscript{2} s\textsuperscript{-1}, and $3.97 \times 10^{-14}$ to $9.10 \times 10^{-14}$ m\textsuperscript{2} s\textsuperscript{-1}, respectively (Rusch and others 2005). The $t_c$ for Cu, Cr, and Zn to stop leaching were 78-254 days, 61-168 days and 89-145 days, respectively (Rusch and others 2005).

The engineering properties test results indicated that the composite material could be classified as well-graded gravel or well-graded sand with little or no fines. The direct shear test determined the angle of internal friction as 49-50° (Rusch and others 2005). The USCS (Unified Soil Classification System) classification would also qualify the PG briquettes as a potential fill material in embankment construction projects because of their excellent workability characteristics.
Economic Analysis and Other Benefits

The economic analysis performed by LSU personnel (Rusch and others 2001, Deshpande 2003) assumed a PG briquette plant located in Riverview, Florida with 4.5 million tons annual briquette production capacity. The projected cost, without factoring the offset cost of PG disposal and raw PG water contents for Louisiana (Baton Rouge) and Florida (Tampa), are listed in Table 1. The selected four PG briquettes are <$15.5·ton$^{-1}$ (maximum value) vs. a local cost of $35·ton$^{-1}$ of granite. The economic analysis does not include the offsetting cost of PG disposal. Typically, PG is disposed of at a cost of $1.5-10·ton$^{-1}$. According to Florida Law (Florida Administrative Code 62-673.650), after March 25, 2001, lined disposal systems are required for new PG stacks. This will increase the PG disposal offset cost, making the PG briquette option more attractive. There are many benefits in moving away from the current method of disposal in stacks, including the reduction in human contact with radon gas, minimized leaching of metals into groundwater supplies, reduction in land space required for PG storage, reduction in legal liability from environmental regulations, and production of a low-profile coastal protection material under $15.5·ton$^{-1}$ (Deshpande 2003).

Table 1. PG Briquette Production Costs.

<table>
<thead>
<tr>
<th>PG:Class C Fly Ash:Portland Type II Cement</th>
<th>Production Cost ($/ton$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Year – 2001</td>
</tr>
<tr>
<td></td>
<td>Florida</td>
</tr>
<tr>
<td>77%:20%:03%</td>
<td>10.15</td>
</tr>
<tr>
<td>73%:25%:02%</td>
<td>10.62</td>
</tr>
<tr>
<td>72%:25%:03%</td>
<td>11.30</td>
</tr>
<tr>
<td>69%:30%:01%</td>
<td>11.10</td>
</tr>
<tr>
<td>68%:30%:02%</td>
<td>11.78</td>
</tr>
<tr>
<td>67%:30%:03%</td>
<td>12.46</td>
</tr>
<tr>
<td>64%:35%:01%</td>
<td>12.26</td>
</tr>
<tr>
<td>63%:35%:02%</td>
<td>12.94</td>
</tr>
<tr>
<td>62%:35%:03%</td>
<td>13.62</td>
</tr>
</tbody>
</table>

Typically, stone, earth, Portland cement concrete, other types of concrete and grouts, structural sheets and metals, wood, plastics, geotextiles and different recycled materials are used in coastal protection devices. Currently, riprap used for erosion control in Florida is brought in by rail at a cost ranging from $31 to $60·ton$^{-1}$ (Henderson 2007). Yearly granite needs for each coastal erosion control project average 10,000 tons (Lowish 2004). In Louisiana, the majority of material used as riprap and for dike construction is limestone mined in Arkansas and barged to the state at a cost of $36-$52·ton$^{-1}$. In Louisiana, there are numerous coastal protection and restoration projects that require on the order of thousands to tens of thousands of tons of rock per project (LDNR 2007).

In addition to the cost, the currently used coastal protection materials have a high “sinkage” coefficient, resulting in a portion of the material being lost to the sediments.
The end result is the need for additional material. In response to the extensive damage and losses caused by Hurricanes Katrina and Rita along the Louisiana coast, the U.S. Army Corps of Engineers (USACE) is charged with developing a comprehensive coastal protection plan with respect to hurricanes. In examining proposed engineering innovations for protective barriers, the USACE recognized that lighter aggregates are needed to reduce the mass of levees placed on weak soils along the Louisiana coast (USACE 2002). Consequently, low-weight, low-profile, and durable materials for use in coastal protection programs are needed. Researchers at Louisiana State University are currently investigating methods for stabilizing PG (Guo and others 1999a, 1999b, 2001; Rusch and Guo 2003; Deshpande 2003; Guo and others 2004) for its use as a fill material in coastal protection devices.

**Regulatory Background**

The Environmental Protection Agency (EPA) published 57 FR 23317 on June 3, 1992. This document, in Part 61--National Emission Standards for Hazardous Air Pollutants (NESHAPs), Subpart R: National Emission Standards for Radon Emissions from Phosphogypsum Stacks, and its subsequent modification on February 3, 1999 (64 FR 5574), states that EPA permits two uses of PG without prior approval: (1) agricultural purposes if Ra\(^{226}\) does not exceed 10 pCi·g\(^{-1}\); and (2) research and development with up to 7,000 pounds per facility for indoor research. Regulations pertaining to these uses are summarized below:

**Sec. 61.204 Distribution and use of phosphogypsum for agricultural purposes.** [64 FR 5574, February 3, 1999]

“Phosphogypsum may be lawfully removed from a stack and distributed in commerce for use in agriculture if each of the following requirements is satisfied:

a. The owner or operator of the stack from which the phosphogypsum is removed shall determine annually the average Ra\(^{226}\) concentration at the location in the stack from which the phosphogypsum will be removed, as provided by Sec. 61.207.

b. The average Ra\(^{226}\) concentration at the location in the stack from which the phosphogypsum will be removed, as determined pursuant to Sec. 61.207, shall not exceed 10 pCi·g\(^{-1}\).

c. All phosphogypsum distributed in commerce for use pursuant to this section by the owner or operator of a phosphogypsum stack shall be accompanied by a certification document which conforms to the requirements of Sec. 61.208(a).

d. Each distributor, retailer, or reseller who distributes phosphogypsum for use pursuant to this section shall prepare certification documents which conform to the requirements of Sec. 61.208(b).

e. Use of phosphogypsum for indoor research and development in a laboratory must comply with Sec. 61.205.”
Sec. 61.205  Distribution and use of phosphogypsum for research and development.
[64 FR 5574, February 3, 1999]

a. “Phosphogypsum may be lawfully removed from a stack and distributed in commerce for use in indoor research and development activities, provided that it is accompanied at all times by certification documents which conform to the requirements of Sec. 61.208. In addition, before distributing phosphogypsum to any person for use in indoor research and development activities, the owner or operator of a phosphogypsum stack shall obtain from that person written confirmation that the research facility will comply with all of the limitations set forth in Sec. 61.206(b).

b. Any person who purchases and uses phosphogypsum for indoor research and development purposes shall comply with all of the following limitations. Any use of phosphogypsum for indoor research and development purposes not consistent with the limitations set forth in this section shall be construed as unauthorized distribution of phosphogypsum.

1. Each quantity of phosphogypsum purchased by a facility for a particular research and development activity shall be accompanied by certification documents which conform to the requirements of Sec. 61.208.

2. No facility shall purchase or possess more than 7,000 pounds of phosphogypsum for a particular indoor research and development activity. The total quantity of all phosphogypsum at a facility, as determined by summing the individual quantities purchased or possessed for each individual research and development activity conducted by that facility, may exceed 7,000 pounds, provided that no single room in which research and development activities are conducted shall contain more than 7,000 pounds.

3. Containers of phosphogypsum used in indoor research and development activities shall be labeled with the following warning: Caution: Phosphogypsum Contains Elevated Levels of Naturally Occurring Radioactivity.

4. For each indoor research and development activity in which phosphogypsum is used, the facility shall maintain records which conform to the requirements of Sec. 61.209(c).

5. Indoor research and development activities must be performed in a controlled laboratory setting which the general public cannot enter except on an infrequent basis for tours of the facility. Uses of phosphogypsum for outdoor agricultural research and development and agricultural field use must comply with Sec. 61.204.

c. Phosphogypsum not intended for distribution in commerce may be lawfully removed from a stack by an owner or operator to perform laboratory analyses required by this subpart or any other quality control or quality assurance analyses associated with wet acid phosphorus production.”
Concerning other uses, EPA establishes that approval is required. For the approval to be granted, certain conditions should be met as detailed below:

Sec. 61.206 Distribution and use of phosphogypsum for other purposes. [57 FR 23317, June 3, 1992]

a. “Phosphogypsum may not be lawfully removed from a stack and distributed or used for any purpose not expressly specified in Sec. 61.204 or Sec. 61.205 without prior EPA approval.

b. A request that EPA approve distribution and/or use of phosphogypsum for any other purpose must be submitted in writing and must contain the following information:

1. The name and address of the person(s) making the request.
2. A description of the proposed use, including any handling and processing that the phosphogypsum will undergo.
3. The location of each facility, including suite and/or building number, street, city, county, state, and zip code, where any use, handling, or processing of the phosphogypsum will take place.
4. The mailing address of each facility where any use, handling, or processing of the phosphogypsum will take place, if different from paragraph (b) (3) of this section.
5. The quantity of phosphogypsum to be used by each facility.
6. The average concentration of Ra\textsuperscript{226} in the phosphogypsum to be used.
7. A description of any measures which will be taken to prevent the uncontrolled release of phosphogypsum into the environment.
8. An estimate of the maximum individual risk, risk distribution, and incidence associated with the proposed use, including the ultimate disposition of the phosphogypsum or any product in which the phosphogypsum is incorporated.
10. Each request shall be signed and dated by a corporate officer or public official in charge of the facility.

c. Use is at least as protective of public health, in both the short term and the long term, as disposal of phosphogypsum in a stack or a mine.”

The Maximum Individual Risk (MIR) from the radon emissions from PG stacks accepted by EPA (1989) was $9 \times 10^{-5}$, and more than 77% of the population within 80 km was exposed to a risk of less than $1 \times 10^{-6}$. These values are lower than the EPA-established acceptable lifetime risk of $1 \times 10^{-4}$ to $3 \times 10^{-4}$. The latter value is based on an earlier NESHAP decision (benzene decision; 54 FR 38044, September 14, 1989). EPA concluded that certain uses of PG may be considered acceptable up to this level of risk (57 FR 23311, June 3, 1992).
Project-Specific Goals

The overall goal of this project is the use of phosphogypsum in an embankment consisting of stabilized PG briquettes and geotextile fabric as the mechanically stabilized fill material and limestone or granite as the armoring for their application in a coastal protection device. This project is linked to FIPR’s Environment and Technology Research Priorities. The specific objectives of this project are: (1) Develop a risk assessment model for a model embankment (small-scale test) and (2) Compile a complete permit application based on provisions of 40 CFR Part 61 for the outdoor research. Additionally, a risk assessment model and permit application for a full-scale structure (embankment) were prepared.

The application was submitted to EPA and contact has been maintained to follow the progress of the application. Also, contact with the Louisiana Department of Environmental quality has been made regarding the need of permits for phosphogypsum outdoor research application on the Louisiana coast.
STRUCTURAL DESIGN

The proper design and implementation of marine structures (dikes, embankments, revetments, riprap, etc.) must consider overall strength and stability. Geogrid and geotextile materials are designed to be integrated with available fill materials. They provide tensile strength to the structure, similar to reinforcing steel in concrete, and they allow the construction of embankments and retaining walls at slopes and heights higher than would be allowed with the original granular materials (Koerner 1998; Abramson and others 2002). Geogrid-reinforced structures can be used in the harsh conditions associated with coastal erosion control and submerged foundation projects. The effectiveness of an embankment depends upon several key variables, including: monolithic high mass and porosity, flexibility and hydraulic stability; durability and long-term tensile capacity of the geogrid; and energy dissipation characteristics. The geogrid-reinforced structure using stabilized PG:Class C fly ash:Portland Type I I cement briquette infill may be used in the coastal applications as core material topped with a limestone armor to adsorb most of the kinetic energy exerted on the structures and protect the stabilized PG fill materials, thus reducing the cost of building and maintaining the structure. There is already a precedent for the use of lightweight aggregates (expanded clay) as substitute for crushed gravel aggregate in highway construction (Lehman and Adam 1959) and on the shoreline along Louisiana’s coastline (Bourg 2001).

SMALL-SCALE TEST

The design of the test structure will be in the form of an embankment with approximately 840 kg stabilized phosphogypsum briquettes (total phosphogypsum content of 650 kg). The test structure will have an armor of limestone with a thickness of approximately 0.15 m. The nominal dimensions of the test structure will be 2.8 m (L), 0.58 m (H), and 2.3 m (W) at the base and 0.3 m wide at the top. Stabilized phosphogypsum briquettes will be placed in geotextile bags (approximately 22-23 kg each) and stacked in a geogrid to form the core of the embankment. Limestone will be used as armoring with an average thickness of 0.15 m.

FULL-SCALE EMBANKMENT

The full-scale embankment will have a total of 500 m$^3$ of stabilized phosphogypsum briquettes, with a total phosphogypsum content of 350 metric tons (378 ton). The embankment will have an armor of limestone with a thickness of 0.15 m. The final design will be developed in accordance with the Coastal Engineering Manual (USACE 2002). The dimensions of the embankment will be 300 m (L), 0.90 m (H), 4.40 m (W) at the base and 1.2 m wide at the top. It should be noted that these are approximate values that may need to be adjusted for the exact location. The PG briquettes will be placed in geotextile bags, as described before. The mechanically
stabilized embankment will cover 0.1-0.2% of the area covered by the nearest coastal protection device.

MATERIALS

Phosphogypsum

Source and Quantity

Raw phosphogypsum will be obtained from the Mosaic (formerly IMC-Agrico) Uncle Sam Plant in Uncle Sam, Louisiana. It is anticipated this project will require approximately 350 metric tons (378 tons) of raw phosphogypsum for the embankment.

Approximately 650 (1430 lbs.) kilograms of raw phosphogypsum will be required for the test structure. Including a safety factor, 900 kilograms (1980 lbs.) is being requested for this small-scale field study.

Average Concentration of Ra\(^{226}\)

Over the years of LSU research, the Ra\(^{226}\) content in the stacks located at the Uncle Sam Plant has been measured several times. In the most recent analysis for which the LSU researchers have data, the level was determined to be 32.3 pCi g\(^{-1}\). This value was used in the risk assessment models. The value is in the range of previous results [17.4 to 33.2 pCi g\(^{-1}\) as reported by EPA (1988) for central Florida; 9 to 54 pCi g\(^{-1}\) from various authors as reported by Papapstefanou and others (2006) for Central Florida; 19 to 46 reported by Laiche and Scott (1991) for Louisiana].

Fly Ash

The Class C fly ash will be obtained from Bayou Ash Inc., Erwinville, Louisiana; raw PG will be obtained from Mosaic’s plant in Uncle Sam, Louisiana; the Portland Type II cement will be obtained from River Cement Co., St. Louis, Missouri; and the geogrid material will be obtained from Tensar Earth Technologies Inc., Atlanta, Georgia. The product guide for the geogrid material and specifications are in Appendix A. The geotextile will be saltwater- and chemical-resistant material with triple layer construction similar to the one offered by Tensar Earth Technologies for coastal protection, or a closely matching product.

Briquettes

The PG briquettes will be fabricated according to one of the compositions found to have the best performance in previous studies. The compositions are: 73%:25%:2%,
67%:30%:3%, 63%:35%:2% and 62%:35%:3% PG:Class C fly ash:Portland Type II cement. Fresh Portland Type II cement will be combined with fresh Class C fly ash and dried/crushed/sieved phosphogypsum.

The appropriate component percentages (Table 2) will be combined in a mechanically operated mixer for eight minutes, and the properly homogenized mixture will then be compacted between two rolls cantilevered on the ends of shafts outside the bearing briquettes at the briquetting machine. The target fabrication parameters are listed in Table 2, and include pressure, moisture content, size, and PG mixture. Feed rates will be tested to choose the commercial optimum fabrication parameters.

**Table 2. Proposed Compositions and Fabrication Parameters of the PG Briquettes.**

<table>
<thead>
<tr>
<th>PG (%)</th>
<th>Class C Fly Ash (%)</th>
<th>Portland Type II Cement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>73</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>67</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>63</td>
<td>35</td>
<td>2</td>
</tr>
<tr>
<td>62</td>
<td>35</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fabrication Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Content (%)</td>
<td>4</td>
</tr>
<tr>
<td>Fabrication Pressure (N·m⁻²)</td>
<td>14.3 × 10⁷</td>
</tr>
<tr>
<td>Solid Density (g·cm⁻³)</td>
<td>2.2</td>
</tr>
<tr>
<td>Mass (g)</td>
<td>19.5</td>
</tr>
<tr>
<td>Volume (cm³)</td>
<td>9.0</td>
</tr>
<tr>
<td>Dimension (mm) (L×W×H)</td>
<td>42.5×23.5×14.5</td>
</tr>
<tr>
<td>Surface Area (cm²)</td>
<td>28.8</td>
</tr>
</tbody>
</table>

The compacting pressure has to be changed according to the corresponding moisture content and briquette size. The target dry density will be 2 g·cm⁻³. For the small-scale test, the briquettes will be sealed in plastic drums to cure at room temperature and 100% humidity for one month before testing. For the embankment, the briquettes will be conditioned in an area close to the fabrication facility, and the humidity will be maintained by spray mist. The Portland Type II cement must be cured to allow the cementitious materials to react and harden properly, as with any cement-stabilized material (e.g., soil cement for road construction).

The curing time for optimal development of strength and chemical stability is 28 days in a saturated atmosphere to allow the appropriate hydration of cement and cementitious materials. The plastic drum system serves this function for our sample size. In a commercial setting, concrete structures are cured in a number of ways, including using a saturated cloth covering, a spray/mist system, etc. Radon will not be measured during this time.
For the small-scale test, the briquettes will be fabricated in the K.R. Komarek Briquetting and Research facility. The conditioning of the PG and the curing and packaging in textile bags of the briquettes will be done at LSU.

For the large-scale embankment, the briquettes will be cured in an industrial setting for four weeks, then bagged and transported to the final installation site.

Geogrid

A containment structure in the form of a geogrid will be used in the fabrication of the test structure and embankment cores. A geogrid consists of a network of integrally connected tensile elements with aperture geometry sufficient to permit significant mechanical interlock with the PG briquette aggregates. The biaxial geogrids under consideration are made using polypropylene with a minimum of 2% carbon black, which provides UV protection. Overall, the material is inert to the chemicals and aqueous solutions found in the natural environment. The mechanical and geometric properties of the geogrid will be considered in the PG mechanically stabilized embankment design (Koerner 1998, Abramson and others 2002).

Geotextile Bags

The briquettes will be contained in geotextile bags to prevent their displacement from the geogrids. These geotextile bags will be made of a chemically resistant polymer material suited for coastal applications.
FACILITY AND EMBANKMENT SITE LOCATIONS

RESEARCH FACILITY

Contact: Dr. Kelly A. Rusch
Louisiana State University
College of Engineering
Baton Rouge, LA 70803
Tel: 225.578.8528
Email: krusch@lsu.edu

Storage and Preparation Room: 116 Old Coastal Studies
Geotechnical Testing: 116 Old Coastal Studies and 1408 Patrick F. Taylor

MANUFACTURING FACILITY FOR THE SMALL-SCALE FIELD STUDY

The phosphogypsum (including fly ash and cement) will be transported to K.R. Komarek Briquetting and Research (a paid service, not a participant in the research).

Contact: Dr. Roman Dec
20 W. M. F. Andrews Drive
Anniston, AL 36207
Tel: 256.831.5741
Fax: 256.831.1331

SMALL-SCALE TEST LOCATION

The small-scale test structure will be located in Orleans Parish, along the south shore of Lake Pontchartrain, Louisiana, adjacent to the University of New Orleans Center for Energy Research and Management. The structure will be in the intertidal zone located in a fenced and gated stretch of the Mississippi River levee. A guard patrol limits the access to the gate, located 175 m from the proposed experimental site. The tentative coordinates of the site are 30° 01’58.1” N, 90° 03’48.9” W.

FULL-SCALE EMBANKMENT LOCATION

One location on the northwest shore of Lake Salvador (Location 1; 29°46’3.32"N, 90°15’18.32"W) and one on the west coast of the same lake (Location 2; 29°46’47.08"N, 90°9’4.82"W) were considered, and Location 2 will probably be used. An aerial photo showing the location of the proposed site can be found in Appendix B. The soil in the designated areas is unconsolidated muck, with high organic content, and is permanently submerged. The margins are flooded periodically. Location 2 is on the side of a manmade waterway (Bayou Segnette), separated from the lake in some sections by an artificial embankment.
In this area, some methods of coastal protection have been explored (i.e., Martin and Green 2007, Raynie and Visser 2002, Curole and others 2002, Lee and others 2000). These efforts are based on dredging and rock embankments. The PG will be a lower-weight and lower-cost alternative for coastal protection projects.
COMPLIANCE AND SAFETY MEASURES

The proposed location for the small-scale test is in Orleans Parish, along the south shore of Lake Pontchartrain, Louisiana, adjacent to the University of New Orleans Center for Energy Research and Management. The test structure will be in the intertidal zone located in a fenced and gated stretch of the Mississippi River levee. A guard patrols the gate that limits the access to the gate, located 175 m from the proposed experimental site.

The full-scale embankment will be located on the side of a man-made waterway (Bayou Segnette), separated from the lake in some sections by an artificial embankment. The area has limited access by land and is mainly accessed by water. The bar that separates the man-made channel from Lake Salvador is too narrow to support any population. The location is used mainly as a waterway to get to adjacent fishing camps.

The LSU research team does not believe that the use of stabilized PG briquettes in the construction of coastal protection devices falls under the auspices of the Marine Protection, Research and Sanctuaries Act (also known as the Ocean Dumping Act). The admixtures (cement and fly ash) are not regulated by this act. All but the top 10 cm of the embankment will be submerged. Wave action at the site will generally be less than 0.30 m except in extreme events, when full submergence of the embankment would likely occur. The PG will be placed in a coastal lake, close to a manmade canal. The LSU research team will work with LDNR and LDEQ in addressing compliance issues as it relates to the amount of PG placed at the site. Whenever PG or PG briquettes are transported, they will be accompanied by a chain of custody, an MSDS and any other documents needed to identify the radiation level and emergency contacts.

PHOSPHOGYPSUM CONTAINMENT IN THE FIELD

Geotextile fabric bags will be used to contain the briquettes. Unlike the liners used for PG stacks, the geotextile will allow the movement of vapor and water across the barrier, while the structure of the material retains any briquettes or pieces as small as 0.1 cm. The briquettes will be under 15 cm (6 in) of limestone or granite. The bags will be placed in geogrids to add structural stability to the embankment.

PHOSPHOGYPSUM CONTAINMENT DURING THE MANUFACTURING PROCESS

The PG will be transported to the briquetting facility adjacent to the Mosaic Uncle Sam plant. After the briquettes are formed, they will be cured on site for four weeks under mist spray and bagged in geotextile bags before transporting them to the embankment placement site.

For the small-scale field study, the raw phosphogypsum will be held in a labeled drum and all specimens will be clearly and distinctly labeled as to content. During the manufacturing process, LSU personnel will retain custody of all product and excess
material. Additionally, safety precautions will be taken to minimize any exposure to humans. For example, anyone handling the briquettes will wear protective equipment such as gloves and a respirator and the fabrication process will be done by automated systems in an industrial setting, with open air circulation.

**MONITORING OF POTENTIAL EXPOSURE**

The potential exposure will be estimated through the small-scale test. Periodic inspection (semiannually) of the structure for the first three years will provide information regarding its integrity.

During the small-scale test, the handling of radioactive material on the LSU campus will be controlled and monitored by the LSU Radiation Safety Office (RSO). All LSU personnel working with phosphogypsum are required to receive radiation training and to wear a radiation badge while working with the material. Conservatively, the annual radiation dose at the site and in the laboratory would be less than the PG landfill workers’ dose of 0.14 mrem·yr⁻¹ and much lower than EPA’s risk criteria (SENES Consultants Ltd. 2002). RSO will conduct quarterly surveys of the laboratories handling the PG to monitor radiation levels and safety protocols. The field site will not be monitored by RSO.
Phosphogypsum contains a variety of radionuclides that can contribute to the radiation exposure risk to people in contact with the material. The radionuclide with the highest concentration is Ra-222 (EPA 1998). Radium and its decay chain contribute mainly α and β radiation (Hofmann and others 2000). Of these, α radiation is significant only if ingested or inhaled as it cannot penetrate skin of clothing. Gamma (β) has high penetration ability and its effect is significant in external or internal exposure. The evaluation of internal dose includes gamma and α radiation and the external or direct exposure, only gamma radiation.

EXPOSURE PATHWAYS

EPA (1999) recognizes three main categories of exposure pathways: inhalation, ingestion and external exposure. Among the inhalation pathways, vapor or gas inhalation, as well as radionuclides in airborne particulates are considered. The International Commission of Radiological Protection recommends the use of a particle size based on an activity median aerodynamic diameter (AMAD) of 1 micron in the absence of specific data (ICRP 1994). The absorption can be further classified as fast, median and slow absorbing, depending on the rate of absorption from the lungs to the bloodstream. Although ICRP (1994) describes the type of absorption for most radionuclides, the uncertainty on this value under specific conditions dictates the calculation of all three and the use of the higher value for modeling purposes.

Ingestion of radionuclides can be through direct soil ingestion, food intake, including meat, fish, invertebrates, plants, milk and water. The ingestion coefficients are calculated on average intakes by age group. Milk is considered separate from other food groups as it is considered that its consumption is linked to risks derived from radioiodine. Due to the size of the project it is not expected that direct food intake will contribute to the radiological risk, although the seafood ingestion was considered in the model. Also, it is not expected that water from the study area will be consumed at any time.

With respect to external exposure, two sources are considered by EPA (1999): exposure to radionuclides in air and exposure to radionuclides in soil; the exposure coefficients from radionuclides in the soil are published for the surface of the ground or for soil contaminated to an infinite depth. Although there may be gender and age differences in the dose, these are not considered. EPA (1993) calculated external dose rates for many radionuclides, based on an adult male receptor.

Several models were considered for the risk assessment and RESRAD (Argonne National Laboratory, U.S. Department of Energy; ANL 2007) was selected. This series of codes were developed for soil contamination with radionuclides, but the flexibility of the scenarios and the option of creating particular libraries of coefficients allow the adaptation of the model to other scenarios. This model uses an infinite depth source that
can be adjusted for a finite depth, instead of the contaminated surface model. This is more applicable to bulk materials, as opposed to thin layer applications. Radiation exposure from air submersion (airborne sources of radiation) is not considered in RESRAD. Also, this model allows for total risk calculations instead of calculations for the particular area of the body impacted, as were used in other models.

The main difference between RESRAD and other models available for radiation risk assessment is the flexibility of RESRAD to evaluate at the same time several variables, and to include area factors specific for each pathway (King and Keil 2006). The model considers several variables to set up the exposure scenarios, including geometry of the contaminated zone, initial radionuclides concentration and density of the material. Also, the model includes separate pathways for external irradiation, ingestion, particle inhalation and radon. The irradiation pathway includes volume of the contaminated zone, air and water sources. The inhalation pathway includes dust, and a separate pathway is calculated for radon. Ingestion can be from food, water or soil (Yu and others 2001). The model has modules that can account for all the exposure scenarios, with the proper considerations. Although the model was developed specifically for radiation concentrations in soil and runoff, we believe that the results are applicable to coastal protection structures if considerations are done for the volume of the water and the diffusion coefficients. The salinity of the water modifies the leaching of the radium, but this difference was addressed substituting the diffusion coefficient in the model for those obtained by Rusch and others (2005). The area where the model lacks some flexibility is in the capacity to include a large volume of water input in the zone. This can be circumvented by applying a large drawdown volume and a large contact area with the aquifer, to simulate a large water flow for scenarios such as the one including the effect of the tide on the embankment.

RESRAD v.6.4 was used to simulate the different exposure scenarios. The model has been used successfully in various reports approved by EPA. Potential exposure from several risk scenarios was included in the assessment.

The risk scenarios for both the small-scale test and the full-scale embankment are described in detail in subsequent sections of this report.

Potential for Direct Radiation Exposure

Direct exposure to gamma radiation is considered in all phases of the collection of PG, processing and briquette manufacturing, transport of the material, installation of the structures, and experimental period. The highest exposure occurs during the embankment construction phase, when it is considered that the personnel will be in contact with the material for 8 hours per day, 5 days a week. The lowest exposure is for the general public using the embankment as a platform for fishing every weekend. Gamma radiation exposure was considered in all scenarios modeled.
Potential for Air Pathway Exposure

Phosphogypsum dust may be created during the project and become suspended in the air, thus posing an inhalation exposure pathway. The moisture used to manufacture the briquettes and the resulting compacted material will serve to greatly reduce the creation of harmful dust. The PG briquettes placed in the field will be in a humid, wet environment and this will further reduce any potential for dust. In the laboratory, dust may be created while the PG and PG briquetting are tested, and personnel will be required to use dust masks and gloves as previously discussed. Dust inhalation was considered only in the conditioning and briquetting scenarios.

Potential for Radon Exposure

Radon (Rn$^{222}$) is the gaseous decay product of Ra$^{226}$, and it has the potential to accumulate in closed spaces wherever PG is stored. When the PG is placed inside, the room will be well ventilated using either a laboratory hood or supplementary fans. The outdoor exposure should be very low in the coastal area due to the high dilution rate and dispersion from persistent coastal breezes. The radon gas exposure was considered in all the scenarios modeled.

Potential for Water Pathway Exposure

The water-dependent exposure calculations are based on the rate of diffusion of the material, the decay rate and the leaching from the briquettes. These variables will be related to the briquettes’ properties and the exposure environment. The research group’s work in this area is described below. The water exposure pathway was considered only in the step related to data collection, as the material will not be subject to water exposure in the other stages.

A statistical model used to decompose the leaching process (based on Fick’s Law) into diffusion, dissolution and immediate dissolution was developed (Guo and others 2004). This model facilitates the prediction of a critical time ($t_c$), after which precipitation exceeds diffusion and leaching out of the stabilized block ceases. This model was used to predict critical times for calcium, sulfate, trace metals and Ra$^{226}$ in previous work, and details of this model are given in subsequent paragraphs.

In previous research (Deshpande 2003), four PG composite combination briquettes screened from nine PG combinations were fabricated at K.R. Komarek Research and Briquetting, Inc. at Anniston, Alabama, and were cured for 28 days at room temperature and 100% humidity prior to subjecting them to any tests. TCLP and dynamic leaching studies, field submergence and cost analyses were conducted on the four composite combinations. The results of TCLP analyses conducted on the raw materials and the four composite combinations showed that the content of As, Cd, Pb and Se in the TCLP extraction fluid was far below the concentration limits set by EPA for declaring a waste to be hazardous (see Table 3; B1: 73%:25%:2%, B2: 67%:30%:3%, B3: 63%:35%:2%, B4: 62%:35%:3%, B5: 63%:35%:2%; Deshpande 2003).
Guo and others (2004) developed a model which considered the nonzero surface concentration and decomposed the dynamic leaching data into three processes: diffusion, dissolution and immediate dissolution.

Assuming a continuous exchange of the leachate medium (saltwater) so that the leaching ion concentrations do not increase in the leachate, which would lead to a change in the fluxes of the leached ions, the one-dimensional flux of the diffusing ion is assumed to follow Fick’s second law:

\[
\frac{dC}{dt} = D_e \frac{d^2C}{dx^2}, \quad 0 \leq t, \quad 0 \leq x \leq \infty
\]  

(1)

where \(C\) (mg·cm\(^{-3}\)) is the calcium/sulfate ion concentration, \(D_e\) (cm\(^2\)·d\(^{-1}\)) is the effective diffusion coefficient, \(t\) (d) is the time and \(x\) (cm) is the one-dimensional coordinate.

The original point (i.e., \(x = 0\)) is in the composite surface with movement into the briquette extending from \(x = 0\) to \(x = +\infty\). This model assumes a uniform distribution of diffused ions within the composite briquette and a constant concentration at the briquette/saltwater interface. Since the leachate is exchanged at a short time interval during the dynamic leaching study, the leaching ion concentration in the leachate can be considered constant. The initial condition is given as:

\[\text{at } t = 0, \quad C = C_o\]  

(2)

where \(C_o\) (mg·cm\(^{-3}\)) is the total initial content in the stabilized solid. The boundary condition is given as:

\[\text{at } x = 0, \quad C = C_1\]  

(3)

where \(C_1\) (mg·cm\(^{-3}\)) is the contaminant concentration at the solid-liquid interface. Considering the given initial and boundary conditions, Equation (1) can be solved as when at \(x = 0\) (Crank 1975):

\[
\frac{C - C_1}{C_o - C_1} = \frac{x}{\sqrt{p \cdot D_e \cdot t}}
\]  

(4)

Table 3. Results of TCLP Leaching Tests with Raw Materials and PG Composites.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>As</td>
<td>1-5</td>
<td>&lt;0.03</td>
<td>&lt;0.03</td>
<td>0.24</td>
<td>0.22</td>
<td>0.16</td>
<td>0.32</td>
<td>5.0</td>
</tr>
<tr>
<td>Cd</td>
<td>0.3-0.4</td>
<td>&lt;0.03</td>
<td>&lt;0.03</td>
<td>0.16</td>
<td>0.12</td>
<td>0.28</td>
<td>0.30</td>
<td>1.0</td>
</tr>
<tr>
<td>Pb</td>
<td>2-11</td>
<td>&lt;0.04</td>
<td>&lt;0.04</td>
<td>0.16</td>
<td>0.10</td>
<td>0.16</td>
<td>0.14</td>
<td>5.0</td>
</tr>
<tr>
<td>Se</td>
<td>1.0</td>
<td>0.24</td>
<td>0.52</td>
<td>0.32</td>
<td>0.14</td>
<td>0.20</td>
<td>0.17</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Differentiating the above equation and substituting it into Equation (1) gives:

\[
\left( \frac{dC}{dt} \right)_{x \to o} = (C_o - C_i) \frac{1}{\sqrt{p \cdot D_e \cdot t}}
\]  

(5)

The flux, \( J(t) \), of diffusing substances at the unit time and unit area through the solid/solution interface is therefore:

\[
J(t)_{x \to o} = (C_o - C_i) \sqrt{\frac{D_e}{p \cdot t}}
\]  

(6)

where \( J \) (mg·cm\(^{-2}\)·d\(^{-1}\)) is the flux of diffusing ions. The cumulative flux, \( f(t) \), of the diffusing ions at the unit time and unit area through the solid/liquid interface is obtained by integrating equation (6) over time (t):

\[
f(t)_{x \to o} = 2(C_o - C_i) \sqrt{\frac{D_e \cdot t}{p}} = K_d(C_o - C_i)\sqrt{t}
\]  

(7)

where, \( K_d \) is the rate constant of the diffusion process and is given by:

\[
K_d = 2\sqrt{\frac{D_e}{p}}
\]  

(8)

Assuming diffusing ions are not involved in any chemical reactions, the cumulative flux is constant with respect to any value of x.

Equation (7) can be used to identify the leaching mechanisms and to calculate the effective diffusion coefficient. Three different leaching mechanisms can be singled out using cumulative contaminant release (mg/cm\(^2\)) as a function of time (leaching period, days): dissolution, surface wash-off and matrix diffusion. The cumulative release when plotted against time on a log-log scale represents release curves with slopes +1, +0.5 and 0 that correspond to the dissolution, diffusion and surface wash-off processes, respectively (de Groot and van der Sloot 1992). Practically, however, it is difficult to obtain the exact slope values of +1, +0.5 or 0, as the leaching process is generally a combination of all of these mechanisms (Guo and others 2003). Therefore, a statistical regression model has been developed by Guo and others (2003) in which the experimentally obtained cumulative fluxes (release rates) were divided into the fluxes of three individual surface wash-off (\( F(t)_{sw} \)), diffusion (\( F(t)_d \)) and dissolution (\( F(t)_{ds} \)) processes as:

\[
F(t)_{sw} = K_{sw}(C_0 - C_1) + e_i
\]  

(9)

\[
F(t)_d = K_d(C_0 - C_1)\sqrt{t} + e_i
\]  

(10)

\[
F(t)_{ds} = K_{ds}(C_0 - C_1) t + e_i
\]  

(11)
where $K_{sw}$ is the rate constant of immediate dissolution, i.e., surface wash-off (cm), $K_d$ is the rate constant of the diffusion process (cm·d$^{-0.5}$), $K_{ds}$ is the rate constant of the long-term dissolution process (cm·d$^{-1}$), $t$ is the time (d) and $e_i$ is the random residual error term. Equations (9), (10) and (11) represent the surface wash-off, diffusion, and dissolution processes, respectively. Also it is assumed that the error term is normally distributed with a zero mean and a common variance (i.e., $\sigma^2$). To check the normality of the error term, four test methods were used: the Shapiro-Wilk, Kolmogorov-Smirnov, Cramer-von Mises and Anderson-Darling (SAS Publishing 2004). The homogeneity of variance for the residual error ($e_i$) was tested using Levene’s test. The error term is considered a standard normal distribution and uniform variance if the tested p-values are $\geq 0.05$. It should also be noted that each of these mechanisms might not occur in a dynamic leaching process separately, but a combination of two or all processes may take part in the leaching mechanism. Thus, a complete model reaction including all processes can then be summarized as:

$$F(t) = K_{sw}(C_o - C_1) + K_d(C_o - C_1)\sqrt{t} + K_{ds}(C_o - C_1)t + e_i \quad (12)$$

Equation (12) was tested to select the simplest best-fit curves having an r-square close to unity. SAS 8.2 was used for regression analyses and the input was the cumulative fluxes obtained from the dynamic leach test.

The use of stabilized composites in the marine environment requires an estimation of the potential for long-term survival that is controlled by both diffusion and surface precipitation. Therefore, the critical time, $t_c$, needed for the precipitation processes to equal and surpass the diffusional processes can be found by differentiating Equation (12) to find the daily flux:

$$f(t) = \frac{K_2(C_o - C_1)}{2\sqrt{t}} + K_3(C_o - C_1) \quad (13)$$

At daily flux $f(t) = 0$,

$$t = t_c = \left(\frac{K_2}{2K_3}\right)^2 \quad (14)$$

where $t_c$ is the time when the rate of diffusion equals that of precipitation. Equation (13) was used to generate the daily flux plot and Equation (14) was used to calculate the critical time ($t_c$). Lower values of $K_3$ and/or the higher values of $K_2$ will result in higher $t_c$ values. In the initial phase ($t < t_c$), the diffusion process dominates the leaching process, and the net daily flux is outward leaching of calcium/sulfate ions. When $t > t_c$, precipitation dominates the leaching process and the net daily flux is precipitation of calcium/sulfate ions. The regression method decomposes the stabilized PG leaching processes (overall reaction) into diffusion, surface wash-off and immediate and long-term precipitation (Guo and others 2004). The overall reaction was calculated by combining diffusion and surface precipitation to obtain the critical time ($t_c$) (Table 4). The $t_c$ is the
minimum number of days at which the briquette leaching process stops. For all the four composite combinations, the critical times (t_c) calculated based on calcium and sulfate concentrations were 108-141 d and 441-879 d for calcium and sulfate, respectively. A representative flux curve is shown in Figure 2.

Table 4. Effective Diffusion Coefficients and Critical Times for the Four PG Combinations.

<table>
<thead>
<tr>
<th>PG:Class C Fly Ash: Portland Type II Cement</th>
<th>t_c (Ra^{226}) (days)</th>
<th>D_e(Ra^{226}) (m^2 s^{-1}) \times 10^{-17}</th>
<th>D_e(Cr^{3+}) (m^2 s^{-1}) \times 10^{-13}</th>
<th>D_e(Cu^{2+}) (m^2 s^{-1}) \times 10^{-13}</th>
<th>D_e(Zn^{2+}) (m^2 s^{-1}) \times 10^{-13}</th>
<th>D_e(Fe^{2+}) (m^2 s^{-1}) \times 10^{-13}</th>
</tr>
</thead>
<tbody>
<tr>
<td>73%:25%:2%</td>
<td>370</td>
<td>2.37</td>
<td>8.85</td>
<td>5.14</td>
<td>3.68</td>
<td>9.37</td>
</tr>
<tr>
<td>67%:30%:3%</td>
<td>148</td>
<td>5.41</td>
<td>9.29</td>
<td>8.92</td>
<td>3.74</td>
<td>9.66</td>
</tr>
<tr>
<td>64%:35%:1%</td>
<td>466</td>
<td>5.67</td>
<td>9.47</td>
<td>7.81</td>
<td>8.12</td>
<td>9.68</td>
</tr>
<tr>
<td>63%:35%:2%</td>
<td>188</td>
<td>3.88</td>
<td>9.33</td>
<td>4.79</td>
<td>4.12</td>
<td>8.36</td>
</tr>
</tbody>
</table>

PG Composite 73%:25%:02%

![Image](image.png)

Figure 2. The Flux Curve for Ra^{226} Indicates That Leaching Will Cease at 370 d.

The concentrations of calcium (n = 3), sulfate(n = 3), toxic metals (n = 3) and Ra^{226} (n = 2) in the leachate collected during the dynamic leaching test were used for calculation of effective diffusion coefficients (D_e) and critical time (t_c) by the newly developed regression model (Guo and others 2004; see Table 4), which was used to identify the leaching kinetics. The lowest Ra^{226} diffusion coefficient (Table 4) from the regression method indicates that Ra^{226} can be diffused out at a very low rate and therefore the radon gas releasing from Ra^{226} decay becomes the only path for a radioactive effect on the environment.

The squares in Figure 2 represent the diffusion component of the K_2(CO_3-C_3)/2t^{0.5} (Equation 13), the circles represent the dissolution/precipitation of the overall regression [i.e., K_3(CO_3-C_1) (Equation 13)], and the triangles represent the sum of these two curves. The point where the overall reaction curve intersects the x-axis represents the critical
time \( (t_c) \). Theoretically speaking, and in the case of radium, the briquettes would stop leaching radium at \( t_c \). Ra\(^{226}\) will stop leaching from the briquettes at 148-466 d for the four composite combinations.

The percent release of the available radium for the tested four combinations was found to be very low (highest value of 0.21-0.26\%). This indicates that more than 99.7% of the initial Ra\(^{226}\) present in the raw PG remained in the stabilized composite (Table 5). Thus, the stabilization technique used in this research resulted in a high degree of effectiveness in immobilizing Ra\(^{226}\).

**Table 5. Leaching Results for All Four PG Briquette Combinations.**

<table>
<thead>
<tr>
<th>PG:Class C Fly Ash:Portland Type II Cement</th>
<th>Initial Ra(^{226}) Content (pCi·g(^{-1}))</th>
<th>Total Ra(^{226}) Available (pCi)</th>
<th>Cumulative Ra(^{226}) Leached (pCi)</th>
<th>Release (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>73%:25%:2%</td>
<td>26.0</td>
<td>508</td>
<td>1.07</td>
<td>0.212</td>
</tr>
<tr>
<td>67%:30%:3%</td>
<td>23.9</td>
<td>466</td>
<td>1.07</td>
<td>0.229</td>
</tr>
<tr>
<td>64%:35%:1%</td>
<td>22.5</td>
<td>438</td>
<td>1.16</td>
<td>0.264</td>
</tr>
<tr>
<td>63%:35%:2%</td>
<td>22.1</td>
<td>431</td>
<td>1.03</td>
<td>0.239</td>
</tr>
</tbody>
</table>
SMALL-SCALE TEST STRUCTURE

QUANTITY OF PHOSPHOGYPSUM AND DESIGN OF THE TEST STRUCTURE

It is anticipated this research will require approximately 650 kilograms of raw dry phosphogypsum (for the outdoor portion of the research). It is expected that the material will have an approximate water content of 20%. Based on this and a small excess to account for unusable briquettes, 900 kilograms are being requested for research in the field. This is based on the geometry of the test structure to be tested, in order to assess the suitability of the material for coastal protection structures. Phosphogypsum density was considered at 1.51 g·cm\(^{-3}\), as this is the average value reported by Tittlebaum and Lea (1990). The briquettes have a compacted density of 1.9 to 2.1 g·cm\(^{-3}\).

The test structure will have an armor of limestone with a thickness of 0.13 m and a base of 0.16 m of the same material. The final design will be developed in accordance with the Coastal Engineering Manual and approved by LDNR. A control test structure will be prepared in the same area. The control structure will be constructed the same as the structure containing PG except limestone aggregate of the same approximate dimensions as the briquettes will be substituted. The control structure is not considered in the risk analysis model as it does not contain any phosphogypsum.

For the model, the dimension of the test structure will be 2.8 meters long, 0.58 meters high, and 2.3 meters wide at the base and 0.3 meters wide at the top. It should be noted that these are approximate values that may need to be adjusted for the exact location. The stabilized phosphogypsum briquette core will have a dimension of 2.18 \(\times\) 0.27 \(\times\) 1.26 m in the shape of a triangular prism (Figure 3). Relative to coastal protective devices in the area, the test structure will cover 0.1-0.2 percent of the area covered by the nearest coastal protection device.

![Figure 3. Schematic Representation of the Proposed Test Structure.](image)

The phosphogypsum briquettes will be fabricated according to the selected formulation of 73% PG, 25% fly ash and 2% Portland cement. The briquettes will be contained in geotextile bags of approximately 0.028 m\(^3\) (1 cu. ft.) and positioned in the
test structure, with 0.15 m of limestone armoring and 0.15 m of limestone base. The structure will be in the intertidal zone, with 1 ft of the structure permanently submerged and the rest exposed. For the model a PG content of 73% in the briquettes was considered. A pore volume of the individual briquettes of 22% (Rusch and others 2005) and a total pore volume of 40% of the briquettes in the structure were considered, according to measurements made in the laboratory.

RADIONUCLIDE CONCENTRATION IN THE PG AND BRIQUETTES

The concentration of radionuclides in phosphogypsum has been measured in several studies (e.g., EPA 1978, EPA 1998, Cohen and Associates 1993). Previous research has shown that the typical concentrations of radon in phosphogypsum from Florida range from 21-33 pCi·g⁻¹ (EPA 1978). For this model, the data from samples obtained from the stacks at Uncle Sam, LA, and analyzed by ARS International (NELAP certificate #E87558) were used (Table 6).

The concentrations in the briquettes were calculated considering the formulation with the highest PG concentration (73%; Table 7). The use of this formulation will give the worst-case scenario for the test structure. The calculations include only the radionuclides contained in the phosphogypsum fraction of the formulation. If other sources of radiation are included, they will have to be recalculated in the model. The final concentrations and activities of each radionuclide will be calculated and included in the model after the final sample is analyzed.

Table 6. Average Radionuclide Concentration in Phosphogypsum from the Stacks at Uncle Sam, LA.

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Concentration</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bq · g⁻¹</td>
<td>pCi · g⁻¹</td>
</tr>
<tr>
<td>U-235</td>
<td>0.02</td>
<td>(0.50)</td>
</tr>
<tr>
<td>Th-228</td>
<td>0.01</td>
<td>(0.33)</td>
</tr>
<tr>
<td>Ra-228</td>
<td>0.02</td>
<td>(0.40)</td>
</tr>
<tr>
<td>Ra-226</td>
<td>0.19</td>
<td>(32.31)</td>
</tr>
<tr>
<td>Pb-210</td>
<td>1.34</td>
<td>(36.18)</td>
</tr>
<tr>
<td>Co-60</td>
<td>0.00</td>
<td>(0.01)</td>
</tr>
<tr>
<td>K-40</td>
<td>0.01</td>
<td>(0.28)</td>
</tr>
</tbody>
</table>
Table 7. Average Radionuclide Concentration in PG Briquettes.

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bq · g⁻¹</td>
</tr>
<tr>
<td>U-235</td>
<td>0.02</td>
</tr>
<tr>
<td>Th-228</td>
<td>0.01</td>
</tr>
<tr>
<td>Ra-228</td>
<td>0.02</td>
</tr>
<tr>
<td>Ra-226</td>
<td>0.19</td>
</tr>
<tr>
<td>Pb-210</td>
<td>1.34</td>
</tr>
<tr>
<td>Co-60</td>
<td>0.00</td>
</tr>
<tr>
<td>K-40</td>
<td>0.01</td>
</tr>
</tbody>
</table>

RISK ASSESSMENT MODEL

The model for the test structure risk considered a contaminated area of 2.75 m² with a depth of 0.3 m. The calculation method was based on volume and no shielding was considered for the armoring material. The whole structure was considered to discharge to the water. The radon diffusion coefficient was considered to be $2.0 \times 10^{-6}$, as this is the average for gypsum reported by Stranden (1988), as cited in Yu and others (1993). It was considered that 6.3 kg·yr⁻¹ of fish and aquatic organisms living in the contaminated area will be consumed after a maximum of 3 days of storage. This consumption represents 35% of the average individual seafood consumption in the US. This is a high value as the experimental area is small. The temperature was considered 16.4°C and the wind speed 4.5 km·h⁻¹ as these are the reported averages for the site. For the transportation scenario, to simulate a polyethylene container the cover set to 12.5 mm (average thickness of the container) and a density of 0.92. The only exposure considered in this scenario was direct radiation.

For the phosphogypsum material, $U^{232}$, $U^{234}$, $Ra^{226}$, $Th^{228}$, $Th^{230}$ and $Pb^{210}$ were considered either directly or as progeny of uranium and radium. Radon gas was considered as a separate product by the model and summed to the projection. The RESRAD model uses the conversion factors from EPA FGR-11 and 12 (Federal Guidance Reports No. 11 and 12; EPA 1988 and EPA 1993) and the slope coefficients from EPA FGR-13 (Federal Guidance Report No. 13; EPA 1999).

The final equilibrium point for radium in the briquettes was shown by previous studies (Rusch and others 2005) to reach equilibrium concentrations between 150-470 d. For this model, the leaching was considered to continue until the end of the experiment that is slightly longer than the time obtained in the leaching studies (540 days). This approach provides a more conservative approach for the risk associated to the general public.
Potential Exposure Scenarios, Pathways and Receptors

Not all the pathways described by EPA (1999, 1993) are relevant for all the exposure scenarios. It is important to define the pathways that will be considered in each scenario, as well as all the scenarios that will be considered on the model. In this study, ten possible scenarios were considered (see Figure 4):

1. Transport of the raw phosphogypsum from the stacks to LSU
2. Sieving and conditioning
3. Transport to briquetting facility
4. Briquetting
5. Transport to LSU
6. Curing at LSU
7. Transport to outdoor test location
8. Construction of the test structure
9. Data collection phase
10. Test structure removal and transport back to the stacks

Although four of the scenarios account for transportation of the material only and are considered to be negligible, they were included in the projections for completeness. It is also important to consider the specific radionuclides that contribute to the risk.

Collection of Phosphogypsum from the Stacks

This step considers the removal of the needed phosphogypsum from Mosaic’s stacks in Uncle Sam, Louisiana. The characteristic of this scenario is that 900 kg of phosphogypsum will be collected directly from the stacks; this can generate dust that may be absorbed by the personnel collecting the material. Also, in this phase a wind speed of 2.44 m·s\(^{-1}\) was considered, as this is the average reported in the area. For this scenario, the following considerations were made:

a. Exposure routes: dust inhalation, direct gamma radiation and radon gas.
b. Potential receptors will be two Mosaic Uncle Sam plant personnel working with the material.
c. Exposure time per person: 4 hours.
d. Major considerations: contaminated zone > 10,000 m\(^2\) and dust formation. For the dust inhalation, a factor of 50 mg/day was considered according to the EPA recommended risk factors (EPA 1997).
Transportation to LSU

After the PG is collected, it will be transported to LSU. In this step, only one LSU employee will participate. The material will be transported in closed containers. The conditions for this scenario are:

a. Exposure routes: direct gamma radiation.
b. Potential receptors: one LSU employee
c. Exposure time: 1 hour
PhosphogypsumSieving and Conditioning

The PG will be sieved and distributed in a layer to dry in an indoor ventilated location at LSU. It is expected that the PG will have an approximate water content of 20%. Two LSU employees will assess daily the condition of the PG. After drying, the PG will be packed again in the transportation containers. An air exchange of .25 per hour is considered. The conditions considered in this step are:

a. Exposure routes: dust inhalation, direct gamma radiation and radon gas
b. Potential receptors: two LSU employees
c. Exposure time per person: 5 days for sieving, 8 hours per day; 0.5 hour per day for 10 days for drying
d. Major considerations: Contaminated zone < 10 m². Potential for high dust formation during the sieving phase. A respiratory combination protection device for particles and gas is considered. A room air exchange of 2.5·h⁻¹ is considered.

Transportation to the Briquetting Facility

The dry PG will be transported to the K.R. Komerak Briquetting and Research Facility in Anniston, Alabama. In this step, three employees from LSU will participate. The material will be transported in closed containers. The conditions for this scenario are:

a. Exposure routes: direct gamma radiation.
b. Potential receptors: three LSU employees
c. Exposure time per person: 10 hours

Briquetting

The dry PG will be mixed with cement and fly ash, according to the composition selected from the four formulations presented in Table 2. These formulations were tested in previous work at LSU (Rusch and others 2005). The mixture will be compacted in briquettes (42.5mm × 23.5mm × 14.5mm).

This step will be performed in the K.R. Komerak Briquetting and Research Facility in Anniston, Alabama. Also, the bagging of the briquettes in geotextile bags with a capacity of 0.028 m³ (1 cu. ft.) will be performed here. Air exchange of .25 per hour is considered. In this process, personnel from LSU and from the briquetting facility will participate. The conditions considered in this scenario are:

a. Exposure routes: dust inhalation, direct gamma radiation and radon gas
b. Potential receptors: three LSU employees and two employees from the briquetting facility.
c. Exposure time per person: 2 days, 8 hours per day.
d. Major considerations: Dry material. Potential for high dust formation during the sieving phase. A respiratory combination protection device for particles and gas is considered. A room air exchange of 2.5·h$^{-1}$ is considered. Dust inhalation was set at 50 mg/day, according to the EPA recommended exposure factor (EPA 1997). Direct radiation and radon gas diffusion were considered to be similar to the unstabilized material even during the bagging phase. This is very conservative as the porosity of the material is reduced roughly by 50% and the compaction is higher. The radiation concentration was reduced according to the amount of PG in the briquette for the last phase. The model was run with the 73% PG concentration.

**Transportation from the Briquetting Facility**

The PG briquettes will be transported from the briquetting facility to LSU by three LSU employees. The briquettes will have a total weight of approximately 890 Kg. The material will be transported bagged and in closed containers. The conditions for this scenario are:

a. Exposure routes: direct gamma radiation
b. Potential receptors: three LSU employees
c. Exposure time per person: 10 hours

**Curing of the Material**

The briquettes in geotextile bags will be set to cure in an indoor ventilated location at LSU. The cement-fly-ash-PG briquettes will need to set before they are installed in the coastal protection structure test structure. For this step, the following considerations were made:

a. Exposure routes: direct gamma radiation and radon gas
b. Potential receptors: two LSU employees
c. Exposure time per person: 30 days, 0.5 hours per day
d. Major considerations: Contaminated zone < 10 m$^2$. Room air exchange of 2.5·h$^{-1}$.

**Transportation to the Test Site**

The geotextile bags with the PG briquettes will be transported from LSU to the south shore of Lake Pontchartrain, where the test structure will be constructed. In this step, three employees from LSU will participate. The material will be transported bagged and in closed containers. The conditions for this scenario are:

a. Exposure routes: direct gamma radiation.
b. Potential receptors: three LSU employees
c. Exposure time per person: 2 hours
Test Structure Construction

The construction step considers the unloading and positioning of the material on the test site. The considerations for this step are:

a. Exposure routes: direct gamma radiation, radon gas
b. Potential receptors: five LSU employees
c. Exposure time per person: 10 days, 8 hours per day
d. Major considerations: No dust production. The exposure be considered continuous during the build phase, but this is a conservative estimate as a large part of the construction time will be consumed on the site preparation and the base and armoring positioning. The actual exposure time while handling the material will probably be less than 1/3 of the total build time. No indoor exposure.

Data Collection

After the structure is positioned, data will be collected for 18 months. In this period, quarterly observations will be made to measure the test structure’s dimensional change (length, width, height, and settlement) with time. Observations will also be made after storm events. Considering the storm events and the quarterly sample events, it is estimated that two LSU researchers will have 2 days of exposure every month. Even when the structure will be in an area with limited human access, the possibility of incidental exposure of 4 hours per week for two persons from the general population was considered. Also, the very unlikely possibility of a person digging out a briquette and accidentally consuming part of it was considered. Leaching coefficients from previous work done at LSU (Desphande 2003) show that leaching is limited to 150-470 days and that it is below $5.5 \text{ m}^2\cdot\text{s}^{-1}$ for all the formulations considered (Table 3).

The considerations for this phase are:

a. Exposure routes: direct gamma radiation, radon gas and minimal ingestion.
b. Potential receptors: two LSU employees and two persons from the general public.
c. Exposure time per person: 18 months, 2 days/month, 8 hours/day for LSU personnel and 72 weeks, 4 hours per week for general public. Ingestion of 1 gram of the briquette in the time of the study is also considered.
d. Major considerations: No dust production. Leaching is $<5.5 \text{ m}^2\cdot\text{s}^{-1}$. No indoor exposure. Ingestion is considered as a single event. No indoor exposure.

Test Structure Removal

At the end of the field study, the coastal protection device will be disassembled and all recovered PG briquettes will be returned to LSU, weighed, and examined. All
unused phosphogypsum and all phosphogypsum products will be collected and returned to Mosaic for disposal at the end of the project. In this phase, it was considered that the risks were the same as those associated with transportation to the site and the construction of the structure, so the considerations are the same as for those two steps summed.

RESULTS – SMALL-SCALE TEST

The excess cancer risks and doses calculated for all scenarios, exposure pathways and receptors are presented in Table 8. The values for the total cancer risk for each scenario were calculated through a continuous graph of the risk vs. time. The individual pathways were approximated from the tables generated by RESRAD, using the year closest to the maximum risk tabulated. The highest risk observed is for workers at the Uncle Sam facility. Although this was considered in the model to assess the total risk, there is no net increase of exposure due to the project, so this probably should not be considered an excess risk due to the application.

Several scenarios that do not require a permit from EPA are included on the simulations. For the regulated scenarios, that will be the construction, removal and sampling period of the test structure the maximum total excess cancer risk was calculated as $1.01 \times 10^{-6}$ for LSU research personnel, including all the exposure pathways and for the general public the exposure is $8.18 \times 10^{-8}$, including all the exposure pathways and the assumption of weekly fishing from the test structure and 35% of the seafood consumption originated from the contaminated zone. This scenario also includes the very unlikely possibility of ingestion of part of the briquettes. The radon diffusion coefficients considered are the same as those for air ($1.1 \times 10^{-5}$). This is an extremely conservative approach, particularly in the case of the briquettes. Depending on the specific composition, porosity and water content this value can have variations in the order of $10^2$ times or more (Yu and others 1993). This variation adds a larger margin of safety to the calculations, as the diffusion will be lower for the briquettes.

The risk to Komarek Research and Briquetting facility personnel would be $7.08 \times 10^{-8}$. This exposure assumes that there is an inhalation of 50 mg·d$^{-1}$ of 1 micron or larger PG dust. Given the operating conditions in the plant, which include the use of respirators, this is a conservative estimate. The maximum dose for these personnel will be $1.35 \times 10^{-1}$ mrem·yr$^{-1}$.
Table 8. Excess Cancer Risk for All Scenarios and Receptors, Small-Scale Test.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Number of Receptors</th>
<th>Receptor</th>
<th>Pathways Considered</th>
<th>Maximum Dose (mrem·yr⁻¹)</th>
<th>Excess Cancer Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation to LSU PG sieving and conditioning</td>
<td>2</td>
<td>LSU worker</td>
<td>External radiation</td>
<td>3.79E-01</td>
<td>2.87E-07</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Inhalation (no radon)</td>
<td>5.52E-05</td>
<td>9.88E-11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Radon inhalation</td>
<td>9.82E-08</td>
<td>1.83E-11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TOTAL</td>
<td>3.79E-01</td>
<td>2.87E-07</td>
</tr>
<tr>
<td>Transp. to briquetting fac. Briquetting</td>
<td>3</td>
<td>LSU worker</td>
<td>External radiation</td>
<td>4.92E-02</td>
<td>3.73E-08</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Inhalation (no radon)</td>
<td>7.00E-03</td>
<td>1.25E-08</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Radon inhalation</td>
<td>2.12E-02</td>
<td>8.40E-12</td>
</tr>
<tr>
<td></td>
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<td>2.51E-01</td>
<td>8.18E-08</td>
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</table>

General public ingestion based on 35% total seafood consumption from contaminated zone.
The calculated excess lifetime cancer risk considering the duration of the experiment based on all exposure scenarios and all radionuclides was $1.01 \times 10^{-6}$ for LSU personnel, with the greatest contribution from the sieving process. This includes inhalation of 50 mg/d of 1 micron or larger PG dust in all the indoor phases of the project as well as in the fabrication and retrieval of the structure from the field site. These values are very conservative as no dust is expected to be generated after the briquetting of the phosphogypsum. The maximum dose for these receptors is 1.35 mrem·yr$^{-1}$.

Also, the use of the structure as a fishing area is unlikely as the area has restricted access. The maximum calculated annual risk to the general public will be $8.18 \times 10^{-8}$. This value is more than 3 orders of magnitude below the $3 \times 10^{-4}$ risk considered and acceptable individual risk by EPA. The maximum dose to a person from the general public under this scenario will be $2.51 \times 10^{-1}$ mrem·yr$^{-1}$. This value is well below the EPA recommended limit of 25 mrem·yr$^{-1}$.

The risk for the general public was calculated including the ingestion of seafood and accidental consumption of part of the briquettes. The fish consumption was considered to be 35% of the total annual average consumption for an individual in the US. The estimate also assumes that the person will be fishing while standing on top of the structure every week the test structure is in place. This value is very conservative, as this high consumption of seafood from the area of influence of the structure is unlikely. Also the use of the structure as a fishing area is unlikely as the area has restricted access.

With respect to the general public, the resulting risk includes ingestion of seafood and accidental consumption of part of the briquettes. The fish consumption was considered to be 35% of the total annual average consumption for an individual in the US. This value is very conservative, as this high consumption is unlikely.

The radon diffusion coefficients considered are the same as those for air ($1.1 \times 10^{-5}$). This is an extremely conservative approach, particularly in the case of the briquettes. Depending on the specific composition, porosity and water content this value can have variations in the order of $10^2$ times or more (Yu and others 1993).

The calculated excess lifetime cancer risk considering the duration of the experiment based on all exposure scenarios, all receptors and all radionuclides was $1.01 \times 10^{-6}$ for LSU personnel, with the greatest contribution from the sieving process. For non-LSU personnel the risk calculated was $7.08 \times 10^{-8}$, due to the small-scale briquetting process. The individual total excess cancer risk for the general public was $8.18 \times 10^{-8}$. This value is more than 3 orders of magnitude below the $3 \times 10^{-4}$ risk considered as a safe maximum individual risk by EPA. Note that if the field activities, including
transportation are included, the risk to LSU personnel is $6.16 \times 10^{-7}$, with a maximum dose of 0.78 mrem·yr$^{-1}$, and there is no risk associated with this activities for non-LSU personnel. The risk for the general public is maintained at $8.18 \times 10^{-8}$.

This model shows that the use of the PG in the proposed structure does not pose an excessive risk to the researchers or the population due to radioactivity. These results were obtained under the extremely conservative conditions used in the model.
FULL-SCALE EMBANKMENT

QUANTITY OF PHOSPHOGYPSUM AND DESIGN OF THE EMBANKMENT

The embankment is anticipated to require 500 m$^3$ of stabilized phosphogypsum briquettes, with a total phosphogypsum content of 350 metric tons (378 tons). It is expected that the material will have a water content of 8%. The amount of PG required is based on the geometry of the embankment. Phosphogypsum density was considered at 1.51 g·cm$^{-3}$, as this is the average value reported by Tittlebaum and Lea (1990). The briquettes have a compacted density of 1.9 to 2.4 g·cm$^{-3}$.

The embankment will have an armor of limestone with a thickness of 0.15 m and a base of 0.15 m of the same material. The final design will be developed accordance with the Coastal Engineering Manual (USACE 2002) and approved by LDNR.

For the model, the dimension of the embankment will be 300 m (L), 0.90 m (H), 4.40 m (W) at the base and 1.2 m wide at the top. The stabilized phosphogypsum briquette core will have a dimension of 300 × 3.0 × 0.6 m in the shape of a triangular prism (Figure 6).

The phosphogypsum briquettes will be fabricated according to the selected formulation. For the model, the formulation was 73% PG, 25% fly ash and 2% Portland cement as this formulation will have the highest amount of PG and hence will provide a more conservative estimation. The briquettes will be contained in geotextile bags of approximately 0.028 m$^3$ (1 cu. ft) and positioned in the embankment, with 0.15 m of limestone armoring and 0.15 m of limestone base. The embankment will be permanently submerged, except the top part of the armoring (0.15 m). A pore volume of the individual briquettes of 22% (Rusch and others 2005) and a total pore volume of 40% of the briquettes in the structure were considered, according to measurements made in the laboratory.

RADIONUCLIDE CONCENTRATION IN THE PG AND BRIQUETTES

As was the case with the model for the test structure, radionuclides data were used from samples obtained from the stacks at Uncle Sam, LA, and analyzed by ARS International (Table 6).

The concentrations on the briquettes were calculated considering the formulation with the highest PG concentration (73%; Table 7) to give the worst-case scenario for the exposure from the embankment. The calculations include only the radionuclides contained in the phosphogypsum fraction of the formulation.
RISK ASSESSMENT MODEL

The model for the embankment risk considered a contaminated area 300 m (L), 0.60 m (H), 3.0 m (W). The calculation method was based on volume and no shielding was considered for the armoring material. The whole structure was considered to discharge to the water. As with the model for the test structure, the radon diffusion coefficient was considered to be $2.0 \times 10^{-6}$ (Stranden 1988, as cited in Yu and others 1993). It was considered that 6.3 kg·yr$^{-1}$ of fish and aquatic organisms living in the contaminated area will be consumed after a maximum of 3 days of storage. This consumption represents 35% of the average individual seafood consumption in the U.S. This is a high value, as the area of influence of the embankment is relatively small. The temperature was considered 16.4°C and the wind speed 4.5 km·h$^{-1}$ as these are the reported averages for the site. For the transportation scenario, to simulate a polyethylene container the cover was set to 3.0 mm (average thickness of the container) with a density of 0.92. The results are very conservative, as the real shielding for the driver will be provided by the metal walls of the load area of the vehicle, which have a higher density and are comprised of several layers of metal. The only exposure considered in this scenario was direct radiation.

Radionuclides and radon gas in the embankment risk assessment model were considered in the same way as those in the model for the small-scale structure. If other sources of radiation are included, they will have to be recalculated in the model.

Potential Exposure Scenarios, Pathways and Receptors

As previously discussed, not all the pathways described by EPA (1999, 1993) are relevant for all the exposure scenarios. The risk assessment for the full-scale embankment was conducted considering four scenarios: briquetting, transport to embankment location, construction of the embankment, and embankment effects in place (see Figure 5).

Briquetting and Conditioning

As with the test structure, the dry PG to be used in the full-scale embankment will be mixed with cement and fly ash, according to the composition selected from the four formulations presented in Table 2. The mixture will be compacted in briquettes of the same size used in the test structure. This step will be performed in a commercial briquetting facility adjacent to the PG stacks. The bagging of the briquettes in geotextile bags with a capacity of 0.028 m$^3$ (1 cu. ft.) will also be performed here. The process will be performed in open air flow. In this process, personnel from the briquetting facility will participate. The conditions considered in this scenario are:

a. Exposure routes: dust inhalation, direct gamma radiation and radon gas
b. Potential receptors: five employees from the briquetting facility.
c. Exposure time per person: 1 month, 8 hours per day.
d. Major considerations: Dry material. Potential for high dust formation during the sieving phase. A respiratory combination protection device for particles and gas is considered. Dust inhalation was set at 50 mg/day, according to the EPA recommended exposure factor (EPA 1997). Direct radiation and radon gas diffusion were considered to be similar to the unstabilized material even during the bagging phase. This is very conservative as the porosity of the material is reduced roughly by 50% and the compaction is higher. The radiation concentration was reduced according to the amount of PG in the briquette for the last phase. Model was run with the 73% PG concentration. The model includes a metal shielding in the automatic briquetting machine and industrial respirator for the operators of the briquetting plant.

**Figure 5. Flow Diagram of the Scenarios Considered for the Risk Assessment of the Embankment Model.**
Transportation to the Embankment Site

The geotextile bags with the PG briquettes will be transported from the briquetting facility to Lake Salvador, where the embankment will be constructed. In this step, one driver will participate. Note that more drivers and lower exposures can be calculated, but this scenario provides the most conservative estimates, as it considers all the risk in one individual. The material will be transported bagged. The conditions for this scenario are:

a. Exposure routes: direct gamma radiation.
b. Potential receptors: one driver
c. Exposure time per person: 2 hours

Embankment Construction

As with the test structure, the final design will be developed in consultation with LDNR and in accordance with the Coastal Engineering Manual (USACE 2002). For the risk assessment, it was assumed that an embankment will be constructed in Lake Salvador, Louisiana, on the side of a man-made waterway (Bayou Segnette), separated from the Lake in some sections by an artificial embankment. The soil in this area is composed mainly of Kenner muck. The soils are in general poorly drained, with high organic content and are flooded the majority of the time (Lee and others 2000).

The embankment will require a total of 500 m$^3$ of stabilized phosphogypsum briquettes, with a total phosphogypsum content of 350 metric tons (378 tons). The embankment will have an armor of limestone with a thickness of 0.15 m. The dimensions of the embankment will be 300 m (L), 0.90 m (H), 4.40 m (W) at the base and 1.2 m wide at the top. It should be noted that these are approximate values that may need to be adjusted for the exact location (Figure 6).

Figure 6. Schematic Representation of the Proposed Embankment.

This step considers the unloading and positioning of the material on the test site. The considerations for this step are:

a. Exposure routes: direct gamma radiation, radon gas.
b. Potential receptors: five LSU employees
c. Exposure time per person: 10 days, 8 hours per day.
d. Major considerations: No dust production. The exposure be considered continuous during the construction phase, but this is a conservative estimate as a large part of the construction time will be consumed on the site preparation and the base and armoring positioning. The actual exposure time while handling the material will probably be less than 1/3 of the total construction time. No indoor exposure.

**Embankment In Situ**

After the structure is positioned, LSU personnel will monitor the structure for 36 months. In this period, semiannual observations will be made to measure regarding the dimensions (length, width, height, and settlement) of the structure. Observations will also be made after storm events. An estimate of two LSU researchers working with 2 days of exposure every month was used for the calculations. Incidental exposure of 4 hours per week for ten persons from the general population was considered. Also, the very unlikely possibility of a person digging out a briquette and accidentally consuming part of it was considered. Leaching coefficients from previous work done at LSU (Desphande 2003) show that leaching is limited to 150-470 days and that it is below $5.5 \text{ m}^2\cdot\text{s}^{-1}$ for all the formulations considered (Table 3), but for the purpose of this risk assessment, the leaching was not limited in time.

The considerations for this phase are:

a. Exposure routes: direct gamma radiation, radon gas and minimal ingestion.
b. Potential receptors: three LSU employees and ten persons from the general public.
c. Exposure time per person: 36 months, 2 days/month, 8 hours/day for LSU personnel and 30 years, 4 hours per week for general public. Ingestion of 36 grams of the briquette per year is also considered for the general public.
d. Major considerations: No dust production. Leaching is .0025 per month. No indoor exposure.

**RESULTS – EMBANKMENT**

The excess cancer risks and doses calculated for all scenarios, exposure pathways and receptors are presented in Table 9. The values for the total cancer risk for each scenario were calculated through a continuous graph of the risk vs. time. The individual pathways were approximated from the tables generated by RESRAD, using the year closest to the maximum risk tabulated. The highest risk observed is for workers at the Uncle Sam facility. Although this was considered in the model to assess the total risk, there is no net increase of exposure due to the project, so this probably should not be considered an excess risk due to the application.
Table 9. Excess Cancer Risk for All Scenarios and Receptors, Full-Scale Embankment.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Number of Receptors</th>
<th>Receptor</th>
<th>Pathways Considered</th>
<th>Maximum Dose (mrem·yr⁻¹)</th>
<th>Excess Cancer Risk</th>
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*General public ingestion based on 35% total seafood consumption from contaminated zone.

The scenarios considered are: briquetting and conditioning of the phosphogypsum, transportation to the embankment site, construction of the embankment and exposure from the embankment on site. The maximum total excess cancer risk was calculated as $6.6 \times 10^{-6}$ for construction workers. The cancer incidence will be $3.3 \times 10^{-5}$ for this group considering five workers, including all the exposure pathways and considering no respirators or special protective clothing are used during the construction.

The individual excess cancer risk for the drivers that will transport the PG and the briquettes was calculated assuming the same person will be doing all the transportation, and the risks for all transportation phases were added. This is conservative as it is unlikely that a single truck will carry all the material. The excess cancer risk and incidence for this receptor was estimated at $2.9 \times 10^{-8}$ and a maximum dose of $3.8 \times 10^{-2}$ mrem·yr⁻¹.

The individual excess cancer risk to briquetting facility personnel will be $3.5 \times 10^{-6}$. The incidence can be expected to be $1.7 \times 10^{-5}$ if five workers are assigned to this duty. This exposure assumes that there is an inhalation of 50 mg·d⁻¹ of 1 micron or larger PG dust. Given the operating conditions in the plant, which include the use of respirators, this is a conservative estimate. The maximum dose for these personnel will
be 4.3 mrem·yr⁻¹. The cancer incidence for this group could be $4.5 \times 10^{-7}$, considering 3 persons.

The calculated excess lifetime cancer risk considering the duration of the experiment based on all exposure scenarios and all radionuclides was $1.5 \times 10^{-6}$ for LSU personnel. This includes inhalation of 50 mg·d⁻¹ of 1 micron or larger PG dust in all the phases of the project. It is considered that LSU personnel will monitor the embankment site for 3 years. These values are very conservative as no dust is expected to be generated after the briquetting of the phosphogypsum. The maximum dose for these receptors is $6.5 \times 10^{-2}$ mrem·yr⁻¹.

The risk for the general public was calculated including the ingestion of seafood and accidental consumption of part of the briquettes. The fish consumption was considered to be 35% of the total annual average consumption for an individual in the U.S and is equivalent to 6.3 Kg of seafood from the contaminated area per year (1.15 pounds per month). The estimate also assumes that the person will be fishing while standing on top of the embankment every week for 30 years, the time that is considered the structure will be in place. This value is very conservative, as this high consumption of seafood from the area of influence of the embankment is unlikely. The scenario also includes the ingestion of 36.5 g·yr⁻¹ of the PG briquettes. The maximum calculated annual risk to the general public will be $6.1 \times 10^{-16}$. The maximum dose to a person from the general public under this scenario would be $1.6 \times 10^{-3}$ mrem·yr⁻¹. This value is well below the EPA recommended limit of 25 mrem·yr⁻¹. The expected excess cancer incidence depends on the number of people with access to the embankment at the same time. It is considered that if 10 people access the embankment all at the same time, the incidence would be $6.1 \times 10^{-15}$.

The radon diffusion coefficients considered are the same as those for air ($1.1 \times 10^{-5}$). This is an extremely conservative approach, particularly in the case of the briquettes. Depending on the specific composition, porosity and water content this value can have variations in the order of $10^2$ times or more (Yu and others 1993).

This model shows that the use of the PG in the proposed embankment does not pose an excessive risk to the researchers or the population due to radioactivity. These results were obtained under the extremely conservative conditions used in the model.
PERMIT APPLICATION SUBMISSION AND INTERACTION WITH EPA

The application package submitted to EPA was prepared as two separate applications and a common background information (see section in this report on Regulatory Background). The application was submitted in January 2009. The research group has been in contact with EPA every 3-4 weeks regarding the status of the application. The submitted application was sent by EPA to an external consultant and is being currently evaluated.

EPA sent the submitted application to the Louisiana Department of Environmental Quality (LDEQ) to evaluate the need of permits for use of the phosphogypsum for outdoor research purposes in the state of Louisiana. The researchers are in contact with LDEQ regarding the status of the application, which is being evaluated.
CONCLUSIONS

The maximum individual risk calculated from the test structure is:

a. $1.1 \times 10^{-6}$ for LSU personnel  
b. $1.5 \times 10^{-8}$ for non-LSU personnel  
c. $3.4 \times 10^{-7}$ for the general public

For the embankment, the risk calculated is:

a. $1.5 \times 10^{-7}$ for LSU personnel  
b. $2.9 \times 10^{-8}$ for drivers  
c. $6.6 \times 10^{-6}$ for construction workers  
d. $3.5 \times 10^{-6}$ for briquetting personnel  
e. $6.1 \times 10^{-16}$ for the general public

The calculated risk for all receptors is well below the EPA’s individual risk criteria of $1 \times 10^{-4}$. The risk values were obtained using a very conservative approach.

The calculated doses due to this project are well below the EPA limits (25 mrem·year$^{-1}$), with a maximum dose of 7.4 mrem·year$^{-1}$ for the construction workers (assumes no protection is used during the construction).

The permit application was submitted to EPA and was in the process of evaluation by an external consultant when this final project report was submitted. The Louisiana Department of Environmental Quality will determine if a permit is required at the state level for the application.
REFERENCES


Product Specification - Structural Geogrid UX TRITON 100

Tensor Earth Technologies, Inc. reserves the right to change its product specifications at any time. It is the responsibility of the specifier and purchaser to ensure that product specifications used for design and procurement purposes are current and consistent with the products used in each instance. Please contact Tensor Earth Technologies, Inc. at 800-636-7273 for assistance.

The structural geogrid shall be an integrally formed grid structure manufactured of a stress resistant high density polyethylene material with molecular weight and molecular characteristics which impart: (a) high resistance to loss of load capacity or structural integrity when the geogrid is subjected to mechanical stress in installation; (b) high resistance to deformation when the geogrid is subjected to applied force in use; and (c) high resistance to loss of load capacity or structural integrity when the geogrid is subjected to long-term environmental stress.

The structural geogrid shall accept applied force in use by positive mechanical interlock (i.e., by direct mechanical keying) with: (a) compacted soil or construction fill materials; (b) contiguous sections of itself when overlapped and embedded in compacted soil or construction fill materials; and (c) rigid mechanical connectors such as bolts, pins or hooks. The structural geogrid shall possess sufficient cross-sectional profile to present a substantial abutment interface to compacted soil or particulate construction fill materials and to resist movement relative to such materials when subjected to applied force. The structural geogrid shall possess sufficient true initial modulus to cause applied force to be transferred by the geogrid to lateral loads without material thinning or stretching of the extruded structure. The structural geogrid shall possess sufficient initial modulus and ribbing rigidity so that a combination of all positive and negative environmental stresses will be adequate for reinforcement of compacted soil or particulate construction fill materials to improve their long term stability. Mechanical load bearing applications such as sewer annular systems. The structural geogrid shall deliver the following characteristics:

<table>
<thead>
<tr>
<th>Product Type</th>
<th>Integrity-Formed Structural Geogrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Transfer Mechanism</td>
<td>Positive Mechanical Interlock</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Product Properties</th>
<th>Units</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Capacity</td>
<td>kN/m²</td>
<td>100 kN/m²</td>
</tr>
<tr>
<td>Structural Integrity</td>
<td>%</td>
<td>95</td>
</tr>
<tr>
<td>Fatigue Strength</td>
<td>%</td>
<td>10</td>
</tr>
<tr>
<td>Dimensional Stability</td>
<td>%</td>
<td>0.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>in.</th>
<th>547 (13.87)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent Open Area</td>
<td>%</td>
<td>80</td>
</tr>
<tr>
<td>Minimum Thickness (any dimension)</td>
<td>in.</td>
<td>0.01 (0.33)</td>
</tr>
</tbody>
</table>

Delivery

The structural geogrid shall be delivered to the job site in not form with each (1) individually identified and randomly measuring 1.05 meters (41.34 feet) in width and 7.2 meters (23.6 feet) in length. A typical loadout quantity is 300 rolls. On special request, the structural geogrid may also be produced to specific engineering designs.

Notes:
1. Unless specified otherwise, values shown are minimum average (MAV) values determined in accordance with ASTM D4766. Brief descriptions of test procedures are given in the following notes. Complete descriptions of test procedures are available on request from Tensor Earth Technologies, Inc.
2. True stress values are derived when initially subjected to a load measured via ASTM D6857 without deforming the material under test until failure.
3. Geogrid transfer capacity measured via ASTM D494-03C, Option 2 using a load rate of 4044.0 kN/m² (900 psi) and 23.6 inches in length by 1 inch in width.
4. Resistance to loss of load capacity or structural integrity when subjected to statically-aggressive environments measured via EPA 600/4 (2002) testing.
5. Resistance to loss of load capacity or structural integrity when subjected to ultraviolet light.

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6651 Glendale Drive, Suite 203
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February 1, 2004

The product specifications supersede all prior specifications for the product described above and is not applicable to any products shipped prior to February 1, 2004.
Product Specification - Structural Geogrid BX1500

Tensor Earth Technologies, Inc. reserves the right to change its product specifications at any time. It is the responsibility of the specifier and purchaser to ensure that product specifications used for design and procurement purposes are current and consistent with the products used in each instance. Please contact Tensor Earth Technologies, Inc. at 800-886-7271 for assistance.

The structural geogrid shall be an integrally formed grid structure manufactured of a stress resistant polypropylene material with molecular weight and molecular characteristics which impart: (a) high resistance to loss of load capacity or structural integrity when the geogrid is subjected to mechanical stress in installation; (b) high resistance to deformation when the geogrid is subjected to applied force in use; and (c) high resistance to loss of load capacity or structural integrity when the geogrid is subjected to long-term environmental stress.

The structural geogrid shall accept applied force in use by positive mechanical interlock (i.e., by direct mechanical keying) with: (a) compacted soil or construction fill materials; (b) contiguous sections of itself when overlapped and embedded in compacted soil or construction fill materials; and (c) rigid mechanical connectors such as bolting, pins or hooks. The structural geogrid shall possess sufficient cross sectional profile to present a substantial abutment interface to compacted soil or particulate construction fill materials and to resist movement relative to such materials when subject to applied force. The structural geogrid shall possess sufficient true initial modulus to cause applied force to be transferred to the geogrid at low strain levels without material deformation of the reinforced structure. The structural geogrid shall possess complete continuity of all properties throughout its structure and shall be suitable for reinforcement of uncompacted soil or particulate construction fill materials to improve their long-term stability in structural load bearing applications such as earth retention systems. The structural geogrid shall otherwise have the following characteristics:

<table>
<thead>
<tr>
<th>Product Type:</th>
<th>Integrimaxy Formed Structural Geogrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Transfer Mechanism:</td>
<td>Positive Mechanical Interlock</td>
</tr>
<tr>
<td>Product Properties:</td>
<td></td>
</tr>
<tr>
<td>Index Properties</td>
<td>Units</td>
</tr>
<tr>
<td>Aperture Diameter</td>
<td>mm (in)</td>
</tr>
<tr>
<td>Minimum Wall Thickness</td>
<td>mm (in)</td>
</tr>
<tr>
<td>Load Capacity:</td>
<td></td>
</tr>
<tr>
<td>True Initial Modulus in Use</td>
<td>kN/m (psi)</td>
</tr>
<tr>
<td>True Tensile Strength @3% Strain</td>
<td>kN/m (psi)</td>
</tr>
<tr>
<td>True Tensile-Strength @3% Strain</td>
<td>kN/m (psi)</td>
</tr>
<tr>
<td>Structural Integrity:</td>
<td></td>
</tr>
<tr>
<td>Jigitation Efficiency</td>
<td>%</td>
</tr>
<tr>
<td>Flexural Stiffness</td>
<td>kN-m/mm (ksi-in/in)</td>
</tr>
<tr>
<td>Aperture Stability</td>
<td>kg-mm/in (lbf-in/ft)</td>
</tr>
<tr>
<td>Durability:</td>
<td></td>
</tr>
<tr>
<td>Resistance to Installation Damage</td>
<td>%</td>
</tr>
<tr>
<td>Resistance to Long Term Degradation</td>
<td>%</td>
</tr>
<tr>
<td>Carbon Black Content</td>
<td>%</td>
</tr>
</tbody>
</table>

Dimensions and Delivery
The structural geogrid shall be delivered in its finished roll form with each roll individually identified and nominally measuring 4.0 meters (13.1 feet) in width and 5.0 meters (16.4 feet) in length. A typical truckload quantity is 350 rolls. On special request, the structural geogrid may also be custom cut to specific lengths or widths to suit site specific engineering designs.

Notes:
1. Unless otherwise specified, values shown are minimum average raw value specifications in accordance with ASTM D-4750. Brief descriptions of test procedures are given in the following notes. Complete descriptions of test procedures are available on request from Tensor Earth Technologies, Inc.
3. True resistance to elongation when initially subjected to a load measured via ASTM D 6687 without deforming test materials under load before measuring such resistance as employing “favorable” or “offset” tangent methods of measurement as an to overstate tensile properties.
5. Resistance to bending force measured via ASTM D-5782-95. using spectrometer with widths two Wide size, with transverse filters cut length with exterior edges of neighbor size to a “dashed”, and at length sufficiently long to enable measurement of the overall dimension. The overall Flexural Stiffness is calculated as the square root of the product of machine and cross-machine-direction Flexural Stiffness-values.
6. Resistance to in-plane inelastic movement measured by applying a 20 kg-moment to the central portion of a 1.5 inch (38 mm) specimen restrained at its perimeter (U.S. Army Corps of Engineers Methodology for measurement of Torsional Rigidity).
7. Resistance to loss of load capacity or structural integrity when subjected to mechanical installation stress in dry core sand (SG), well graded sand (SG), and covered stone classified as poorly graded gravel (SP). The geogrid shall be sampled in accordance with ASTM D5158 and load capacity shall be measured in accordance with ASTM D7690.
8. Resistance to loss of load capacity or structural integrity when subjected to chemical aggressive environments measured via IAPA 3020 Immersion testing.

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February 1, 2004

This product specification supersedes all prior specifications for this product described above and is not applicable to any products shipped prior to September 1, 2004.
Product Specification – Geogrid Composite GC654050

Tensor Earth Technologies, Inc. reserves the right to change its product specifications at any time. It is the responsibility of the specifier and purchaser to ensure that product specifications used for design and procurement purposes are current and consistent with the products used in each instance. Please contact Tensor Earth Technologies, Inc. at 800-836-7211 for assistance.

The geogrid composite is designed specifically for use in marine applications. It shall be an integrally formed grid structure manufactured of a stress resistant polypropylene material, adhesive-bonded to a calendared, woven, monofilament polypropylene geotextile. The geogrid shall have molecular weight and molecular characteristics which impart: (a) high resistance to loss of load capacity or structural integrity when subjected to mechanical stress in installation; (b) high resistance to deformation when subjected to applied force in use; and (c) high resistance to loss of load capacity or structural integrity when subjected to long-term environmental stress such as UV exposure or submergence in saltwater.

The geogrid composite shall accept applied force in use by positive mechanical interlock (i.e. by direct mechanical keying) with: (a) bedding stone or similar; (b) contiguous sections of itself when overlapped and embedded in bedding stone or similar; and (c) mechanical connectors such as hooks, pins, hooks or HDPE/PP braid. The geogrid composite shall possess sufficient cross sectional profile to present a substantial abutment interface to particulate construction fill materials such as bedding stone, and to resist movement relative to such materials when subject to applied force. The geogrid composite shall possess sufficient tensile rigidity to help maintain intimate contact of the geotextile with the underlying material when bedding stone, riprap, or armor stone is placed on top of the geogrid composite. The geogrid composite shall possess sufficient tensile rigidity to resist applied force to be transferred to the geogrid at low strain levels without material deformation of the reinforced structure. The geogrid composite shall possess complete continuity of all properties throughout the structure and shall be suitable for use with bedding stone, riprap, and armor stone materials in coastal and watershed environments, and to improve the long-term stability of coastal structures such as rubble mound breakwaters, jetties and groins.

The geogrid composite shall otherwise have the following characteristics:

Product Type: Integrally Formed Geogrid Composite

Product Properties (Geogrid)

<table>
<thead>
<tr>
<th>Index Properties</th>
<th>Units</th>
<th>MD Values</th>
<th>XMD Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Diameter</td>
<td>mm (in)</td>
<td>49.18 (1.97)</td>
<td>49.00 (1.9)</td>
</tr>
<tr>
<td>Perforated Open Area</td>
<td>%</td>
<td>70</td>
<td></td>
</tr>
</tbody>
</table>

Load Capacity

<table>
<thead>
<tr>
<th>Index Properties</th>
<th>Units</th>
<th>MD Values</th>
<th>XMD Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>True (Unit) Modulus @1% Strain</td>
<td>kN/m (psi)</td>
<td>410 (59,100)</td>
<td>430 (61,300)</td>
</tr>
</tbody>
</table>

Structural Integrity

<table>
<thead>
<tr>
<th>Index Properties</th>
<th>Units</th>
<th>MD Values</th>
<th>XMD Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus</td>
<td>kN/m (psi)</td>
<td>21.5 (3,140)</td>
<td>21.5 (3,140)</td>
</tr>
<tr>
<td>Tensile Stiffness</td>
<td>kN/m (psi)</td>
<td>760 (109,000)</td>
<td></td>
</tr>
<tr>
<td>Torsional Stiffness</td>
<td>kg·m²/deg</td>
<td>8.0</td>
<td></td>
</tr>
</tbody>
</table>

Durability

<table>
<thead>
<tr>
<th>Index Properties</th>
<th>Units</th>
<th>MD Values</th>
<th>XMD Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance to Installation Damage</td>
<td>% GP</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>Resistance to Long Term Degradation</td>
<td>%</td>
<td>88</td>
<td></td>
</tr>
</tbody>
</table>

Product Properties (Geotextile)

<table>
<thead>
<tr>
<th>Index Properties</th>
<th>Units</th>
<th>MD Values</th>
<th>XMD Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (ASTM D-4353)</td>
<td>Lbs</td>
<td>176</td>
<td>76</td>
</tr>
<tr>
<td>Trapped Water Test (ASTM D-4691)</td>
<td>Lbs</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>Percent Open Area (CWW-211220)</td>
<td>%</td>
<td>10.1±1.0</td>
<td></td>
</tr>
<tr>
<td>Apparent Opening Size (AOB)</td>
<td>US G ge</td>
<td>30-50</td>
<td></td>
</tr>
<tr>
<td>Permeability (ASTM D-4491)</td>
<td>Sec</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>Strength Retained (500 hours) (ASTM D-4353)</td>
<td>%</td>
<td>82</td>
<td></td>
</tr>
</tbody>
</table>

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(800) 836-7211

February 1, 2004

This product specification supersedes all prior specifications for the product described above and is not applicable to any products shipped prior to February 1, 2004.
Product Specification – Geogrid Composite GC654050

Tensor Earth Technologies, Inc. reserves the right to change its product specifications at any time. It is the responsibility of the specifier and purchaser to ensure that product specifications used for design and procurement purposes are current and consistent with the products used in each instance. Please contact Tensor Earth Technologies, Inc. at 800-836-7271 for assistance.

Dimensions and Delivery
The geogrid composite shall be delivered to the jobsite in roll form with each roll individually identified and nominally measuring 3.7 meters (12.0 feet) in width and 50.0 meters (164 feet) in length. On special request, the geogrid composite may also be custom cut to specific lengths or widths to suit site-specific engineering designs.

Notes
1. Unless indicated otherwise, values shown are minimum average roll values determined in accordance with ASTM D-4759. Brief descriptions of test procedures are given in the following notes. Complete descriptions of test procedures are available on request from Tensor Earth Technologies, Inc.
3. True resistance to elongation when initially subjected to a load measured via ASTM D8837 (tested at 10 percent per minute based on the greater of 2 or 3.75 inches [60 or 95 millimeters] gauge length) without deforming test materials under load before measuring such resistance or employing "percent" of "offset" in length method, as applicable, to determine tensile properties.
4. Load rupture capability measured via GMIE- shear test, Option A, using specimen dimensions of 9.54 millimeters in length by 0.685 millimeters in width.
5. Resistance to in-plane direction movement measured by applying a 20-degree moment to the central portion of a 3.0 inch x 3.0 inch specimen restrained by permanent 3.0 inch, Army Corps of Engineers Methodology for measurement of "To parisity".
6. Resilience to loss of load carrying or structural integrity when subjected to mechanical stress in installation measured via: ASTM D5818 for "To grade" (SG = 1.67), "To grade" (SG = 1.67), "To grade" (SG = 1.67), and "To grade" (SG = 1.67) with partial load (GP).
7. Resistance to loss of load carrying or structural integrity when subjected to chemical-aggressive environments measured via: EPA-600C immersion testing.

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February 1, 2004
This product specification supersedes all prior specifications for the product described above and is not applicable to any products shipped prior to February 1, 2004.
Appendix B

PROJECT SITES
Figure B-1. Relative Locations of the Proposed Project Sites: (A) LSU Research Facilities; (B) Mosaic Uncle Sam Plant; (C) Komarek Briquetting and Research Facility; (D) Proposed Small-Scale Test Location; (E) Proposed Embankment Location.
Figure B-2. Mosaic Uncle Sam Plant. PG Stacks Located to the West.
Figure B-3. Proposed Location of the Small-Scale Test.
Figure B-4. Lake Salvador Is the Proposed Location of the Embankment.
Figure B-5. The Proposed Embankment Location Is on the East Side of Lake Salvador.
Figure B-6. The Proposed Embankment Will Be Close to an Actual Coastal Protection Project.