

NASA/TM—2006–214197



# **Evaluation of Alternative Refractory Materials for the Main Flame Deflectors at KSC Launch Complexes**

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August 2006

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August 2006

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## ABSTRACT

The launch complexes at John F. Kennedy Space Center (KSC) are critical support facilities required for the safe and successful launch of vehicles into space. Most of these facilities are over 25 years old and are experiencing deterioration. As deterioration of the materials in the launch complex continues, the chance of these deteriorated materials failing and breaking from their base structures during launches increases. When these materials fail and break away from the steel base structure during a launch, the exhaust from the launch vehicle often turns these materials into high-speed projectiles. These projectiles can jeopardize the safety of the launch complex and vehicle. Materials that exhibit long-term resistance to the Florida coastal environment and the launch environment are needed to ensure safe launches at KSC.

Although investigations at the launch complexes have identified several material deterioration problems, this report focuses only on the refractory materials used to protect the steel base structure from the high temperatures during launches. Only one refractory material is currently qualified for use at KSC. An analysis of test data taken from 1981 to 1993 indicates that this refractory material does not meet the requirements of KSC-SPEC-P-0012, *Specification for Refractory Concrete* (1979). In fact, the testing during this period indicated that none of the submitted refractory products could meet the existing specifications. Review of the current specification and required testing indicates that the test methods and qualification requirements are not well defined. As such, the only qualified material for use at KSC does not meet the required specifications, and other, possibly better-performing, materials have not been qualified because of the poorly defined specification tests and requirements. Trejo and Calle (2004) recommended a suite of tests to evaluate refractory materials in the laboratory and developed qualification parameters for the safe use of refractory materials in the launch complexes at KSC. This document reports the outcome of preliminary testing of two refractory products and proposes a plan to generate information on the environmental conditions in the flame deflectors during launches.

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## EVALUATION OF ALTERNATIVE REFRACTORY MATERIALS FOR THE MAIN FLAME DEFLECTORS AT KSC LAUNCH COMPLEXES

### 1 INTRODUCTION

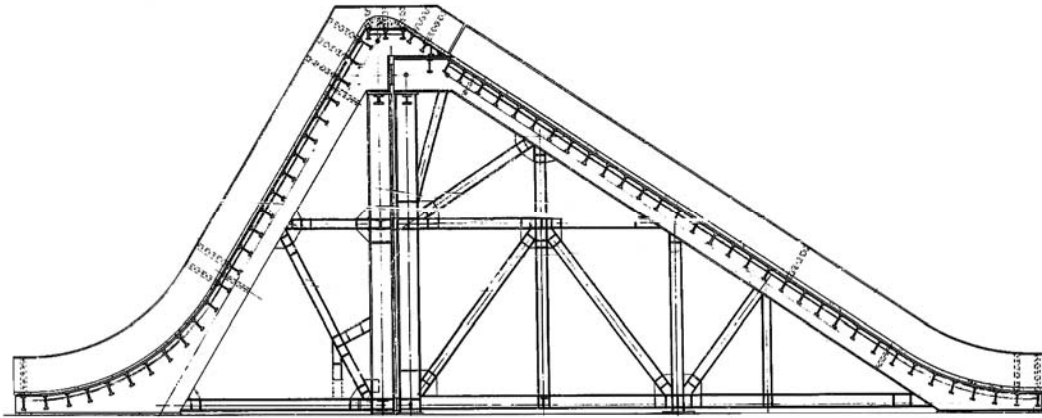
Refractory materials are suitable for use at elevated temperatures and consist of hydraulic cement as a binding agent. Refractory materials have been used mainly where adjacent structures need to be protected from heat and blast, mainly in the flame deflectors and other areas of the launch complexes at John F. Kennedy Space Center (KSC). With age and an increasing number of launches, areas containing the refractory concrete have become more susceptible to failure during launch operations. These failures have resulted in large pieces of refractory materials being projected at high speeds during launches. These large projectiles jeopardize the safety of the launch mission; therefore, better-performing materials are needed.

Outdated material specifications and limited guidance on repair and rehabilitation procedures have raised concerns regarding the performance and safety of the refractory materials used in the launch complexes at KSC, with specific concern associated with Launch Complex 39 (LC-39), where the current space vehicles are launched. This report provides an overview of refractory concrete materials and the existing specifications at KSC for refractory concrete, reviews recommendations made by Trejo and Calle in 2004 for developing a new specification for refractory products, presents findings from pre- and postlaunch inspections of the flame deflectors, defines a methodology to generate information on environmental conditions in the flame deflectors during launches, and presents test data from two refractory products following the procedures recommended in the 2004 report. Future work will include implementing the installation of sensors to define the exposure environment and further testing and validation of the test procedures of refractory materials.

### 2 REFRACTORY-CONCRETE BASICS

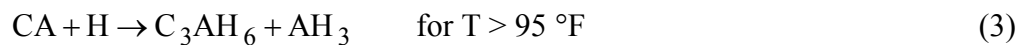
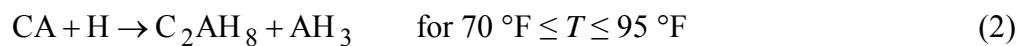
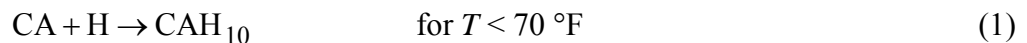
Refractory materials typically contain calcium aluminate cement (CAC). Unlike conventional portland cement (PC) concrete, which spalls and loses integrity when heated, CAC loses strength at moderate heats but gains strengths when exposed to higher temperatures. Because of this, CAC is a popular material used for refractory applications. One major use of refractory concrete materials at KSC is in flame deflector systems. A schematic of the flame deflector system at LC-39 is shown in Figure 1. Flames, exhaust, and loosened materials are channeled through these deflector systems to prevent them from bouncing back and hitting the launch complex and vehicle. The flame deflection system is 490 ft long, 58 ft wide, and 40 ft high (see [http://www.nasa.gov/mission\\_pages/shuttle/launch/Flame-trench-deflector.html](http://www.nasa.gov/mission_pages/shuttle/launch/Flame-trench-deflector.html)). One side of the system was designed to deflect the flames and exhaust from the Orbiter's main engines, and the other side was designed to deflect the flames and exhaust from the two Solid Rocket Boosters (SRBs). The SRBs burn at approximately 3,000 °F, and the exhaust from the main engines burns at lower temperatures. The higher temperatures of the SRB exhaust lead to more severe exposure conditions, resulting in more damage to the deflector unit exposed to this exhaust. The ability to safely meet the requirements of diverting the flames, exhaust, and other small items loosened during a launch is dependent on the integrity and performance of the refractory materials used in

these deflector units. Therefore, it is imperative to use materials that withstand the actual conditions during a launch.



**Figure 1. Cross section of flame deflector units for LC-39A.**

CAC concretes differ from ordinary PC concrete in that the products that form from the reactions between the cement and water (H) are dependent on the temperature and time. The products of CAC reactions are as follows:



Because the  $CAH_{10}$  and the  $C_2AH_8$  are metastable, with time or when the CAC concrete is exposed to moderate heat, these phases will convert to  $C_3AH_6$ . This conversion results in a 52.5-percent and 33.7-percent volume reduction from the  $CAH_{10}$  and  $C_2AH_8$ , respectively. When these conversions occur, the porosity of the CAC concrete increases and the mechanical properties decrease. It should be noted that the strength characteristics of CAC are typically at their lowest values when the CAC is exposed to temperatures sufficient to dehydrate the hydraulic bond, i.e., during the drying phase. However, if the CAC is heated to higher temperatures (typically between 1,600 and 2,500 °F), ceramic bonding occurs and higher strengths are achieved (ACI 547R-70). For all applications, water should be removed from the CAC microstructure prior to high-temperature exposure to eliminate the possibility of spalling and thermal-shock failure.

### 3 EXISTING SPECIFICATIONS FOR REFRACTORY CONCRETE AT KSC

The most recent KSC specification for refractory concrete was published on April 25, 1979. This specification provides requirements for refractory concretes used to protect the flame deflector units and surrounding areas from heat and blast. The specification includes a qualification process, required material characteristics, minimum fresh- and hardened-material requirements, quality assurance provisions, and packing requirements.

The quality assurance section provides information on how manufacturers could qualify their products for use at KSC. The general process includes making test specimens according to the specification and exposing these specimens to an actual launch environment. Requirements for the acceptance of refractory concrete materials used at KSC include the following:

- shall have a 7-day compressive strength of 4,500 psi,
- shall have a 24-hour strength of at least 90 percent of the 7-day strength,
- shall be workable when placed,
- shall resist degradation of thermal-protection characteristics caused by seacoast exposure,
- shall not crack or spall after exposure to a launch environment,
- shall not “erode” more than 1/8 inch after exposure to a launch environment, and
- shall have a maximum heat flux of 3,300 Btu/ft<sup>2</sup>-sec.

A test program was conducted to investigate the performance of refractory materials from approximately 1981 to 1993. The objective of the test program was to qualify alternative materials for use in and around the launch complexes at KSC. The material qualified for use prior to this testing program was Fondu Fyre. Although this material did not meet the minimum requirements of the KSC specification, this material is still used in the flame deflector units.

The following limitations of the existing KSC specifications have been identified:

- Manufacturer are required to provide samples to KSC for testing. These samples are likely cast, dried, and fired, as is common with refractory products. However, refractory concrete in the flame deflector units typically is not exposed to any curing regime, to drying, or to sintering. Performance of the tested samples and as-placed materials is likely to vary significantly.
- Such key performance parameters as the material’s propensity to crack are not included.
- No guidance or requirements on material storage are provided. CAC can hydrate with time under storage conditions that can significantly change the performance of the material.
- No guidance or requirements are provided on placement procedures, curing, or other key construction practices.
- No methodology is provided for qualifying materials.

#### 4 SUMMARY OF 2004 INVESTIGATION

An investigation of the qualification program for refractory products used in the flame deflector units at KSC was performed in the summer of 2004 (Trejo and Calle). The investigation identified key material characteristics that should be evaluated as part of the qualification process. An experimental design and a proposed test program for qualifying materials were developed.

The investigation identified the key performance characteristics of refractory concrete used in the flame deflectors to be abrasion/erosion, shrinkage, thermal properties, compressive strength, modulus of rupture, and splitting tensile strength. Table 1 shows the test methods for each characteristic requiring evaluation.

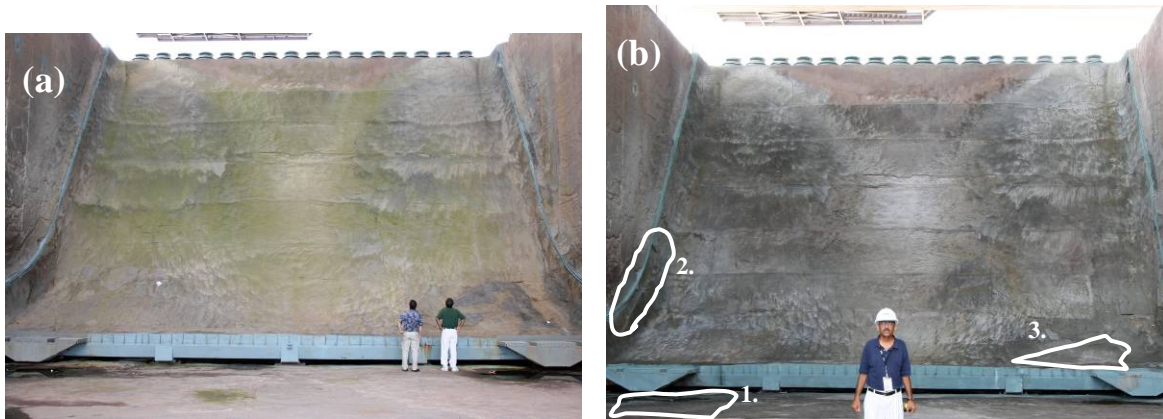
**Table 1. Proposed standard test methods for assessing refractory materials.**

<b>Material Characteristic</b>	<b>Proposed Standard Test Method</b>
Abrasion/Erosion	ASTM C704, <i>Standard Test Method for Abrasion Resistance of Refractory Materials at Room Temperature</i>
Shrinkage/Thermal Expansion	ASTM C531, <i>Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, Monolithic Surfacing, and Polymer Concretes</i>
Compressive Strength	C133, <i>Standard Test Methods for Cold Crushing Strength and Modulus of Rupture of Refractories</i>
Modulus of Rupture	ASTM C583, <i>Standard Test Method for Modulus of Rupture of Refractory Materials at Elevated Temperatures</i> , and ASTM C133, <i>Standard Test Methods for Cold Crushing Strength and Modulus of Rupture of Refractories</i>
Tensile Strength	ASTM C496, <i>Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens</i>

To provide a minimum level of confidence in the performance of different refractory products, an experimental design was proposed. This experimental design will provide reliable analysis of the results at some predetermined confidence levels and intervals, and an unbiased assessment of the refractory-material performance. It is critical that the qualification process use a properly planned experimental program and analysis to select higher-performing refractory products without bias.

#### 5 PRE- AND POSTLAUNCH INSPECTIONS OF FLAME DEFLECTOR

The flame deflectors at LC-39B were inspected prior to and after the STS-113 launch. The inspections included visual observations of cracking, spalling, and abrasion/erosion patterns. The degree of abrasion/erosion that occurred during the launch could not be determined from visual inspections. However, locations that were damaged prior to the launch showed significantly more damage after the launch. Figures 2 through 4 show pre- and postlaunch conditions.



**Figure 2. (a) LC-39B SRB flame deflector prior to launch of STS-113; (b) LC-39B SRB flame deflector after launch of STS-113 (numbers show select locations of damage; see closeup photos in Figures 3 and 4).**



**Figure 3. Location 1 shown in Figure 2(b): (a) prior to launch of STS-113; (b) after launch of STS-113 (note that spalled area has increased significantly).**



**Figure 4. Location 2 shown in Figure 2(b): spalled refractory was approximately 4 inches thick.**



**Figure 5. Location 3 shown in Figure 2(b): note spalling and heavy abrasion/erosion.**

## 6 ENVIRONMENTAL CHARACTERIZATION OF LAUNCH CONDITIONS IN FLAME DEFLECTOR

The objective of sampling, or the placement of sensors on a structure, is to reliably assess the mean and upper limits of the environmental parameters in the flame deflector. To make an inference on the mean environmental parameter, a representative random sampling from the structure needs to be collected. Two questions need to be answered to be able to strategically place the sensors: what should be the total number of sensors installed ( $n$ ), and where should the sensors be placed? Typically, to avoid introducing bias into the process and to initially generate an estimate of the mean and standard error, a select number of sensors are placed in the structure via some chance mechanism (i.e., random placement). For example, if the structure is initially divided into 50 areas, a random-number generator could be used to select 5 to 10 of these areas in which to place a sensor.

After the initial set of sensors has been installed, the user can determine the sample mean,  $\bar{X}$  from the data points  $n$ . This sample mean can then be used as an estimate of the real mean value of the precursor (e.g., in this case, the temperature and load). It should be noted that the sample mean value  $\bar{X}$  is dependent on the location of the sensors and the fact that each different set of placement locations will have a different sample mean value  $\bar{X}$ . Thus, the sample mean  $\bar{X}$  for the initial specific sensor locations selected would actually be one value of a distribution. This distribution is referred to as the sampling distribution. If the precursor values from the launch structure have a normal probability distribution with a mean value  $\mu$  and standard deviation  $\sigma$ , then the sampling distribution of  $\bar{X}$  is a normal distribution with mean  $\mu$  and standard error  $\sigma/\sqrt{n}$ .

In this case, two challenges exist. Information is not available to determine if the precursor values are normally distributed, nor is the value of the standard deviation  $\sigma$  known. These values are needed to determine the degree of confidence in the system. If sufficient sensors were placed ( $n \geq 30$ ), then based on the central limit theorem, one can safely assume that the sampling distribution of  $\bar{X}$  is normal. However, because of the high cost of instrumentation, especially for elevated temperatures in the flame deflectors, it is unlikely that more than 30 strain gauges will be installed (although the limited time for obtaining the data may result in more sensors being placed). If the number of sensors installed is small and the standard deviation  $\sigma$  is unknown, it must be assumed that the precursor values are normally distributed, and this assumption has to be checked after collecting the data. The simplest method to check this assumption is to generate a quantile-quantile plot.

If a random sample of size  $n$  from a normal distribution is assumed with an unknown mean  $\mu$  and unknown variance  $\sigma^2$ , then the number of sensors required that has a  $t$ -distribution with  $n-1$  degrees of freedom would be

$$T = \frac{\bar{X} - \mu}{\frac{S}{\sqrt{n}}} \quad (4)$$



$S$  is the standard deviation of the sample. Based on this distribution, a  $100 \times (1 - \alpha)$  confidence interval can be set on the mean ( $\mu$ ) by

$$\bar{X} - t_{\alpha/2, n-1} \frac{S}{\sqrt{n}} \leq m \leq \bar{X} + t_{\alpha/2, n-1} \frac{S}{\sqrt{n}} \quad (5)$$

where  $t_{\alpha/2, n-1}$  is the upper  $100 \times \alpha/2$  percentage point of the  $t$ -distribution with  $n-1$  degrees of freedom and  $\alpha$  is the probability of  $\mu$  falling outside of this confidence interval. This value can be obtained from a standard  $t$ -distribution table or from an Excel spreadsheet (the  $TINV(\alpha, n-1)$  function).

Equation 5 shows that the confidence interval is symmetrical around the sample mean  $\bar{X}$ . The half-length of the confidence interval  $E$  measures the precision of testing, where lower values of  $E$  indicate better precision. Increasing the confidence level of the interval (decreasing  $\alpha$ ) leads to an increase of the  $t$  value, which leads to an increase of the length of the confidence interval. Therefore, precision of the estimation and the confidence level are inversely related for a fixed sample size  $n$  and standard deviation  $S$  of the collected data. The objective should be to select a confidence interval that is small enough to ensure reliability such that economic decisions for future maintenance, repair, or rehabilitation can be made.

Equation 5 can be modified using the half-length interval  $E$  as follows for the sample size  $n$ :

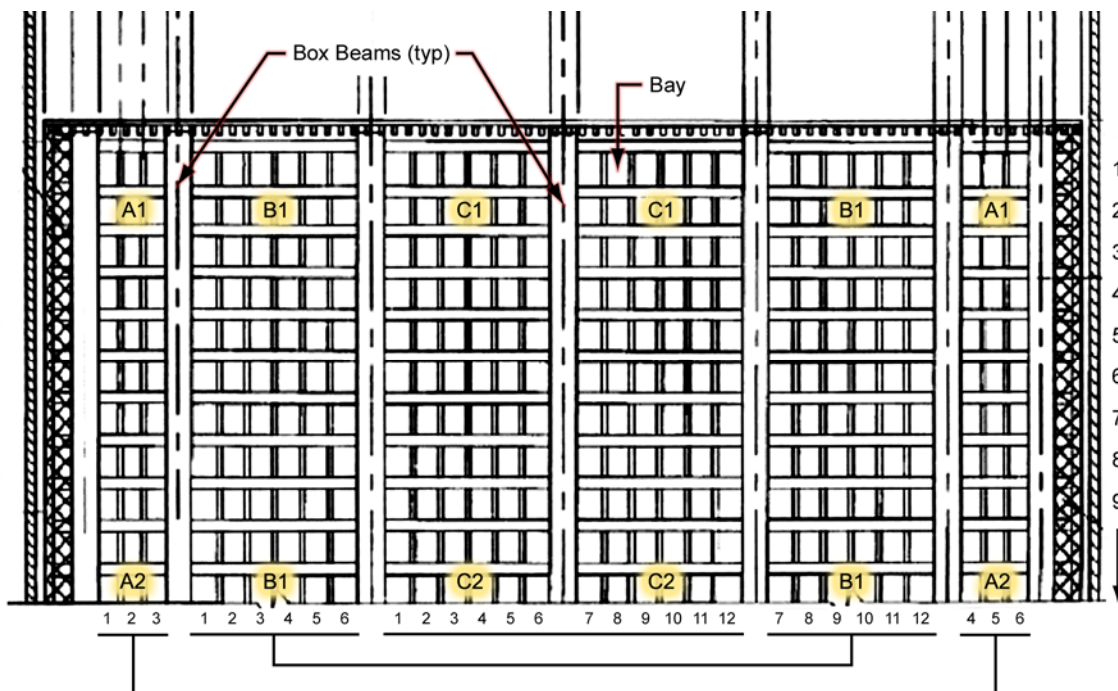
$$n = \left( \frac{t_{\alpha/2, n-1} \times S}{E} \right)^2 \quad (6)$$

It is important to note that (6) is not a definite formula for the sample size  $n$  since the  $t$  value on the right side of the equation is a function of  $n$ . Another important implication of (6) is that the sample size  $n$  is directly related with the standard deviation of the observed sample. The greater the variance in the collected sample, the higher the number of samples required for the same confidence level and precision of testing. Therefore, when data are collected from the launch structure, it may be better to divide the structure into more uniform areas by considering the major sources of variability and then to collect random and independent representative samples from each of these areas. This method should allow the user to reach the desired confidence level and precision with fewer sensors, therefore resulting in more economical use of resources.

Figure 6 shows the plan view of the steel structural frame for the SRB flame deflector. Because the objective is to determine environmental condition (i.e., temperature) and loadings on the flame deflector during a launch and the SRB exhaust directly impacts the outer edges, the area near the top of the flame deflectors will be divided into subareas defined by perimeter lines longitudinal and transverse to the center of the flame (i.e., parallel and perpendicular to the exhaust flow). The longitudinal perimeter lines will be the outer-edge areas (A), the intermediate outer areas (B), and the inner areas (C). The transverse perimeter lines will be defined by the outer edge of the upper bays of the structure and the outer edge of the lowest bays (23 bays). Because the exhaust impacts the upper part of the flame deflectors, these will be subdivided into two subsections, 1 and 2. The division line between these subsections will be the upper edge of

bay 10 (see Figure 6). This will result in six subareas for sensor placement. Locations for sensors will be identified from each subarea. Three strain gauges and three thermocouples will be installed in each subarea. The strain gauges and thermocouples will be placed in the same bays identified.

Area A1 has a total of 60 bays, A2 has 66 bays, B1 has 120 bays, B2 has 132 bays, C1 has 120 bays, and C2 has 132 bays. A total of 18 strain gauges and 30 thermocouples will be installed. The installation locations are shown in Figure 6 (A1, B1, and C1 locations only) and Table 2. Strain gauges should be installed at the center of the transverse beam on the bottom surface for the beam located at the upper edge of the area. Thermocouples should be placed in the refractory concrete above the direct center of the bay. If necessary, refractory concrete should be placed around the thermocouples. Six of the 18 locations for the thermocouples will have three thermocouples installed: one near the upper surface of the refractory concrete (1 inch below the surface), one at the center of the refractory, and one near the bottom of the refractory (approximately 1 inch above the steel plate). These locations are identified in Table 2 with an asterisk (\*).



**Figure 6. Plan view of SRB flame deflector, showing gridlines for environmental and loading characterization.**

**Table 2. Location of sensor sets.**

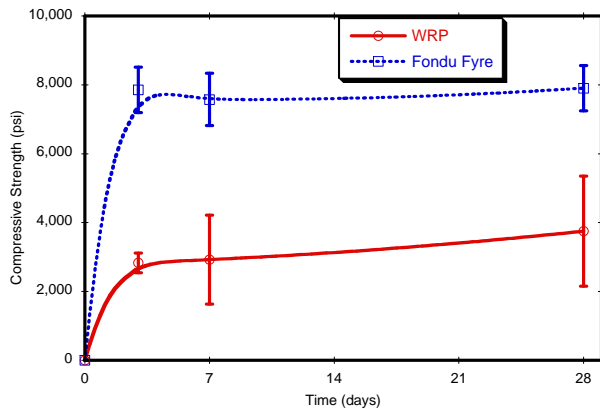
Gauge No. (Area)	Location (Bay No.)	Gauge No. (Area)	Location (Bay No.)
1 (A1)	2 (6)	10 (B2)	5 (17)
2 (A1)*	1 (3)	11 (B2)	1 (19)
3 (A1)*	4 (4)	12 (B2)	12 (11)
4 (A2)	5 (14)	13 (C1)	2 (1)
5 (A2)*	2 (17)	14 (C1)	4 (8)
6 (A2)	1 (11)	15 (C1)*	2 (10)
7 (B1)	9 (3)	16 (C2)	7 (21)
8 (B1)	4 (4)	17 (C2)*	10 (11)
9 (B1)*	12 (4)	18 (C2)	3 (16)

\* Locations where thermocouples will be installed: one near the upper surface of the refractory concrete (1 inch below the surface), one at the center of the refractory, and one near the bottom of the refractory (approximately 1 inch above the steel plate).

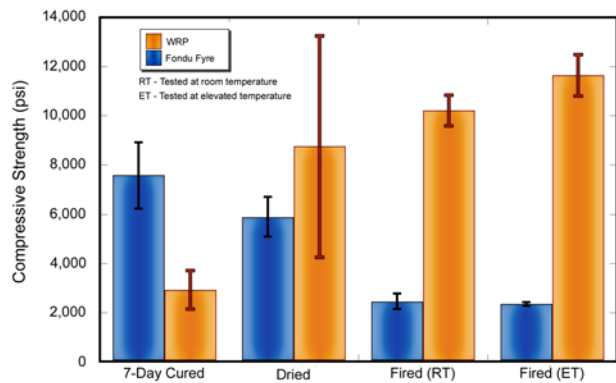
**7 PRELIMINARY TEST RESULTS AND ANALYSIS**

The experimental program consisted of evaluating two refractory products in three conditions: cured, dried, and fired. The products were WRP-Xcel Cast 70 and Fondu Fyre. Cured samples were cast, demolded, and kept moist until the test time (3, 7, and 28 days). The dried samples were cured for 24 hours and then placed in an oven at 225 °F for approximately 24 hours. Samples were allowed to cool in the oven until the following day. The fired samples were cured for at least 24 hours, dried for 24 hours, and then heated to 1,800 °F and 225 °F for approximately 20 hours. Compressive-strength and modulus-of-rupture (MOR) data were obtained for samples that were cooled after the firing (fired – room temperature [RT]) and for samples that were removed from the oven and immediately tested (fired – elevated temperature [ET]).

All refractory materials were cast according to the manufacturer’s recommendations. The maximum water content recommended by the manufacturer was used. Materials were weighed and batched on a scale with an accuracy of 0.003 oz. Mixing was performed with a mixing head connected to a rotary drill in large plastic containers. Care was taken to ensure the mixture was homogenous. Figures 7 through 14 show the results of the investigation.



**Figure 7. Compressive-strength values of two cured refractory products.**



**Figure 8. Compressive-strength values of two refractory products with different processing.**

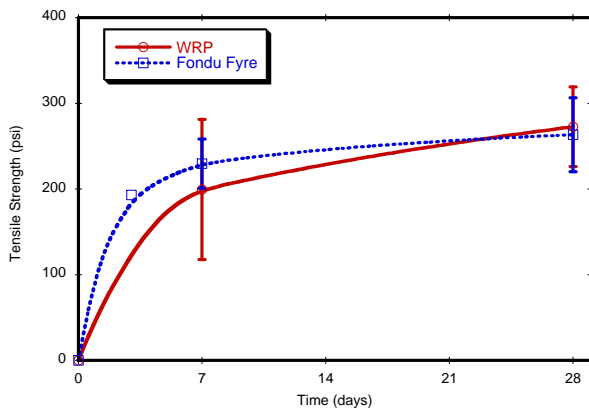


Figure 9. Tensile-strength values of two cured refractory products.

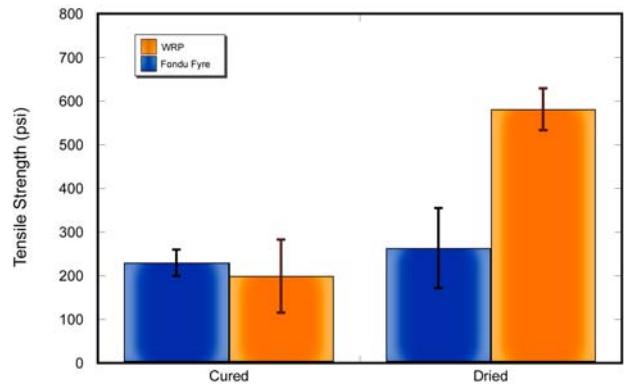


Figure 10. Tensile-strength values of two refractory products with different processing.

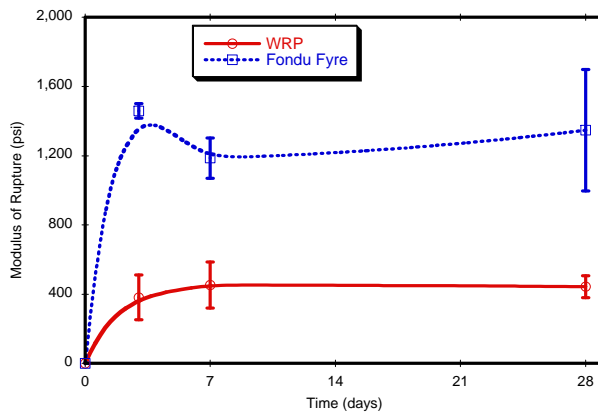


Figure 11. MOR-strength values of two cured refractory products (28-day results not yet available).

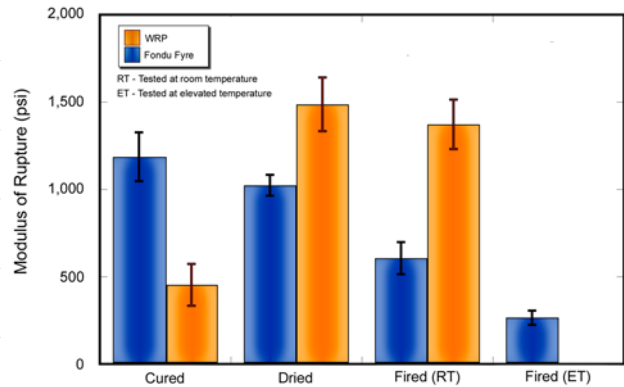


Figure 12. MOR-strength values of two refractory products with different processing.

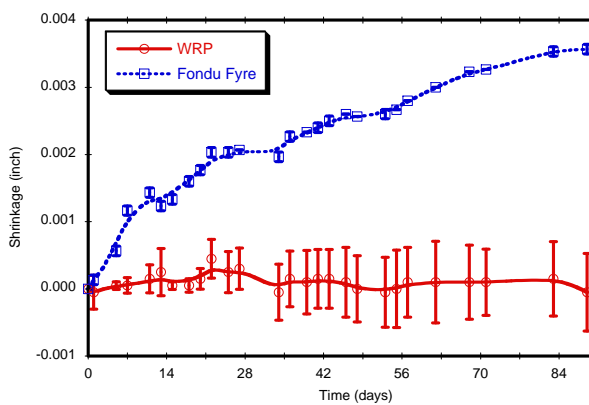


Figure 13. Shrinkage measurements of two refractory products.

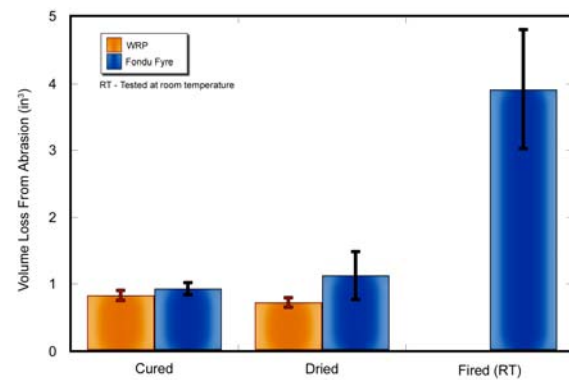


Figure 14. Abrasion results for two refractory products with different processing.

Early-age compressive-strength results from cured samples indicate that Fondu Fyre has higher compressive strengths than WRP. However, when heated, Fondu Fyre rapidly loses strength, whereas the compressive strength of WRP increases significantly when subjected to heat. Both products exhibited similar tensile-strength values at all times tested when cured under standard conditions. However, the tensile strength of WRP increased when subjected to moderate heat (225 °F). Fondu Fyre exhibited similar tensile-strength values when cured and when heated to 225 °F. The MOR for Fondu Fyre when exposed to standard curing exhibited higher tensile strength values than WRP. However, Fondu Fyre exhibited significant loss of capacity when heated (~ 80 percent). The MOR of WRP increased in strength when subjected to moderate heat and exhibited results similar to the samples tested at 225 °F when heated to 1,800 °F.

In test, Fondu Fyre samples exhibited significantly more shrinkage than did WRP. This is critical since postlaunch investigations have identified significant abrasion at cracked areas. Larger shrinkage values will likely lead to more cracking. Abrasion results indicate that WRP resists abrasion better than the Fondu Fyre when subjected to standard curing, and when cured and heated to 225 °F. Samples were not available for evaluating the abrasion resistance of WRP after firing, and comparisons under these conditions cannot be made at this time. However, it should be noted that drying and firing the Fondu Fyre increase the abrasion of this material. Further testing is needed to confirm these findings.

With the exception of the compressive strength and MOR for cured samples, the performance of WRP exceeded that of Fondu Fyre. Because the performance of the Fondu Fyre decreased when exposed to heat, the research team contacted the manufacturer. The manufacturer suggested that the refractory material used in the research may have been old, thus reducing the performance characteristics. This material was obtained from NASA personnel from material that was to be used for repairs on the launch pad. When a new batch of Fondu Fyre is ordered, it is recommended that the new materials be provided to the researchers to investigate their performance.

## **8 SUMMARY**

Refractory materials are developed and designed to resist the deleterious effects of high temperature. To obtain this resistance, refractory materials must be cured, heated, and fired. The refractory products in the flame deflectors at KSC are performing poorly. Extensive repairs are required after every launch. The KSC specification for refractory products defines a process for qualifying new refractory products. Unfortunately, the requirements are ill-defined and no products have ever been qualified (the current product was grandfathered into the list of qualified products). A new specification for qualifying refractory is needed. To ensure the performance of other refractory products used in the flame deflectors, it is proposed that the environment and loads imposed on the flame deflector unit be characterized. The number and locations of strain gauges and thermocouples proposed to characterize this environment are shown in this report. After these data are collected, an analysis can be performed to determine if the environment was sufficiently characterized.

The refractory product currently used at KSC exhibits poor performance when subjected to elevated temperatures. One alternative material showed significant improvements in characteristics when subjected to elevated temperatures. For an immediate benefit, it is

recommended that serious consideration be given to waiving the existing qualification specification. Other materials, potentially better-performing materials, could be identified and comprehensively assessed to compare their characteristics with those of the existing product. In addition, it is recommended that a comprehensive review and revision of the specification for refractory concrete be initiated and additional refractory products be assessed. Preliminary work presented in this report shows that higher-performance materials are readily available. By evaluating and, if appropriate, qualifying new materials for use in the flame deflectors at KSC, it is anticipated that the cost of the materials will decrease. The cost of the KSC-qualified material is 40 to 50 times that of conventional concrete. A significant savings could be achieved by qualifying other products.

Finally, because refractory products are supposed to be cured, dried, and heated to maximize performance, it is recommended that alternative construction practices be used to place the refractory system in the flame deflectors. A precast panel system, fabricated offsite, dried, fired, and installed on the flame deflectors would probably significantly improve the performance of the existing system and would allow for the rapid replacement of damaged panels. The current system of mixing and placing the refractory products is difficult for the labor force, time-consuming, and costly, and it results in an inferior product.

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**REPORT DOCUMENTATION PAGE**

*Form Approved*  
*OMB No. 0704-0188*

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1. REPORT DATE (DD-MM-YYYY) <b>31-08-2006</b>		2. REPORT TYPE <b>Preliminary</b>		3. DATES COVERED (From — To)	
4. TITLE AND SUBTITLE <b>Evaluation of Alternative Refractory Materials for the Main Flame Deflectors at KSC Launch Complexes</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) <b>(1) Calle, Luz Marina</b> <b>(2) Trejo, David</b> <b>(3) Rutkowski, Justin</b>				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>(1) NASA Applied Technology Directorate</b> <b>Kennedy Space Center, Florida 32899</b>  <b>(2,3) Texas A&amp;M University</b> <b>College Station, Texas 77843</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) <b>National Aeronautics and Space Administration</b> <b>Washington, DC 20546-0001</b>				10. SPONSORING/MONITOR'S ACRONYM(S) <b>NASA</b>	
				11. SPONSORING/MONITORING REPORT NUMBER <b>NASA/TM-2006-214197</b>	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Unclassified – Unlimited</b> <span style="float: right;"><b>Distribution: Standard</b></span> <b>Subject Category:</b> <b>Availability: NASA CASI (301) 621-0390</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The deterioration of the refractory materials used to protect the KSC launch complex steel base structures from the high temperatures during launches results in frequent and costly repairs and safety hazards. KSC-SPEC-P-0012, Specification for Refractory Concrete, is ineffective in qualifying refractory materials. This study of the specification and of alternative refractory materials recommends a complete revision of the specification and further investigation of materials that were found to withstand the environment of the Solid Rocket Booster main flame deflector better than the refractory materials in current use in terms of compressive strength, tensile strength, modulus of rupture, shrinkage, and abrasion.					
15. SUBJECT TERMS <b>refractory materials</b>					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>UU</b>	18. NUMBER OF PAGES <b>26</b>	19a. NAME OF RESPONSIBLE PERSON <b>Luz Marina Calle</b>
					a. REPORT <b>U</b>







