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Refractory Materials for Flame Deflector Protection System Corrosion Control: Flame Deflector Protection System Life Cycle Cost Analysis Report

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Executive Summary

A life cycle cost (LCC) analysis was performed to meet the requirements of the Constellation Architecture Requirements Document (CARD) General Program Policy. The objective of this sub-element of the task, Refractory Materials for Flame Deflector Protection System Corrosion Control, was to perform an LCC analysis that compares the operational LCC, processing/ turnaround timelines, and operations manpower inspection/ repair/ refurbishment requirements for corrosion protection of Kennedy Space Center Launch Pad Flame Deflector associated with the existing cast-in-place materials and a newer advanced refractory ceramic material. The LCC analysis for the launch pads included costs associated with all damage and potential damage resulting from refractory foreign object debris, the costs for repairing the refractory concrete in the flame deflectors, the damage resulting to the steel base structure caused by refractory concrete cracking or failure, planning and engineering costs associated with the flame deflector repair, and other potential costs. It is anticipated that advanced refractory materials would provide corrosion protection of critical program operational assets which reduces LCC by reducing corrosion failures, decreasing the need for maintenance, and minimizing the environmental impact of corrosion protection.

Reports on the results of four surveys and three trade studies were submitted to the Technology Development Program, Advanced Capabilities Division, Exploration Systems Mission Directorate prior to the LCC analysis report. Reports on the following surveys were submitted on January 16, 2009:

- Refractory Coating Systems Literature Survey
- Refractory Ceramics Literature Survey
- Refractory Material Commercial Off-the-Shelf (COTS) Vendors
- Similar Industries and/or Launch Facilities Surveys

Reports on the following trade studies were submitted on January 23, 2009:

- Metal Flame Deflector (with no refractory material) versus New Refractory Materials
- In-place Curing, Drying, and Sintering of Current Refractory Material versus New Refractory Material
- COTS versus Refractory Material Requirements for Flame Deflector

The LCC analysis compared the estimated costs of three alternatives for solving the problems caused by the current refractory materials used to protect the flame trench: (1) Continued use of the current refractory material without any changes; (2) Completely reconstruct the flame trench using the current refractory material; (3) Completely reconstruct the flame trench with a new high performance refractory material. The costs for the 20 year analysis were estimated based on an analysis of the amount of damage that occurs after each launch and an estimate of the average repair cost. Alternative 3, developing and implementing a new refractory material, was found to save $32 million compared to alternative 1 and $17 million compared to Alternative 2 over a 20 year life cycle.

A sensitivity analysis was performed to determine which variables most affect the cost savings data. The average repair cost was found to have a significant effect on the cost savings. A conservative rate of $300/ft^2$ was used in the analysis and was based on data provided in interviews with engineers that oversee the repairs. If the cost and area of the recent repairs on the trench walls is used, a repair cost of $600/ft^2$ is calculated. If this value is used, the total savings of Alternative 3 increases to $55 million. Sensitivity analysis in the amount of damage occurring, the number of Shuttle launches and the cost of reconstruction of the entire flame trench are presented and discussed.

The economic analysis indicated that the payback period for the research investment to develop an alternative new refractory material would be 7 years and that the savings to investment ratio is 3.2. Potential benefits associated with the improved safety associated with use of the new material were not included in the analysis because they are unquantifiable. Inclusion of these safety benefits would decrease the payback period and increase the savings to investment ratio. Significant benefits can be realized with the development of a new refractory ceramic material.

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Acronyms and Symbols

°C	degree Celsius
CARD	Constellation Architecture Requirements Document
COTS	commercial off-the-shelf
CxP	Constellation Program
DPP	discounted payback period
ETDP	Exploration Technology Development Program
FOD	foreign objects and debris
ft	foot
FY	fiscal year
GOP	ground operations project
GSE	ground support equipment
K	thousand
KSC	Kennedy Space Center
LC 39A	Launch Complex 39A
LC 39B	Launch Complex 39B
LC	launch complex
LCC	life cycle cost
M	million
MFD	main flame deflector
NASA	National Aeronautics and Space Administration
NPV	net present value
SFD	side flame deflector
SIR	savings to investment ratio
sq	square
SRB	solid rocket booster
SSME	Space Shuttle main engine
STS	Space Transportation System
USA	United Space Alliance

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1 INTRODUCTION

During the Technology Prioritization Panel held in December 2007, the Constellation Program (CxP) Ground Operations Project (GOP) identified corrosion control technologies as their #2 technology need for the initial capabilities required to meet the Draft Stretch/Operability requirements for reduced ground processing complexity, streamlined integrated testing, and operations phase affordability. To address this technology need, the Exploration Technology Development Program (ETDP) project, *Refractory Materials for Flame Deflector Protection System Corrosion Control,* was formulated to develop replacement refractory materials that exhibit long-term resistance to degradation and will enable supportability at Kennedy Space Center (KSC) launch facilities and ground systems through increased operational life cycles.

The launch complexes at KSC are critical support facilities required for the safe and successful launch of vehicles into space. Most of these facilities are over 40 years old and are experiencing deterioration. As deterioration of the materials in the launch complex continues, the chance of these deteriorated materials becoming a launch debris safety hazard increases. As a result of the constant deterioration from launch heat/blast effects and aggressive environmental exposure, the refractory materials currently used at the launch pad flame deflectors have become very susceptible to failure, resulting in large pieces of refractory materials breaking away from the steel base structure. These pieces are projected at high speed during launch, and jeopardize the launch complex, vehicle, and safety of the crew.

Replacement refractory systems must be developed to withstand the extremely corrosive environment at the launch pads caused by the highly corrosive hydrochloric acid and heat/blast effects that are generated by the solid rocket boosters (SRB) during a launch. Advanced technologies for the corrosion protection of launch pad flame deflectors are necessary to address these problems, which significantly impact ground processing and launch safety.

1.1 Background

NASA uses refractory concrete to protect the steel base structure of the flame deflectors that receive and deflect the flames and exhaust from the SRBs and Space Shuttle main engines (SSME) during launch, thereby protecting the Space Shuttle and surrounding facilities. The current refractory concrete material, Fondu Fyre®, was developed solely for NASA, and is the only material available for use. However, it does not meet qualification requirements of the current specification, KSC-SPEC-P-0012 (April 25, 1979). Fondu Fyre was grandfathered into the qualified products list; was never tested for resistance to SRB acidic exhaust; and loses strength as a function of time. Refractory material failures, the size of the damaged area, the loss of strength, and frequency, cost, and extent of repairs are increasing with every launch. The continued use of this product has resulted in NASA spending significant effort and capital to repair the refractory concrete protective lining and the steel base structure. In addition to increased efforts and costs, the failure of the refractory concrete during launch results in foreign objects and debris (FOD) that can damage ground support equipment (GSE) and the Shuttle. Figure 1 clearly shows the extent of degradation to Fondu Fyre.

Figure 1. Degradation to Fondu Fyre on the SRB Flame Deflector

Over the last two years, significant liberation of refractory material in the flame trench adjacent trench walls, following Space Shuttle launches, have resulted in extensive investigations of failure mechanisms, load response, ejected material impact evaluation, and repair design analysis (environmental and structural assessment, induced environment from SRB plume, loads summary, and repair integrity), assessment of risk posture for flame trench debris, and justification of flight readiness rationale. Although the configuration of the launch pad, water and exhaust direction, and location of the Mobile Launcher Platform between the flame trench and the flight hardware should protect the Space Shuttle Vehicle from debris exposure, loss of material could cause damage to a major element of the ground facility (resulting in temporary usage loss), and damage to other facility elements is possible. The near term actions for the Shuttle Program are to fix the problem to allow for subsequent planned launches and monitor the problem throughout the remainder of the Program. These are all significant risks that will be inherited by Ground Operations for Constellation and development of new refractory material systems is necessary to reduce the likelihood of the FOD hazard during launch.

Thus for Constellation Ground Operations, developing replacement refractory materials will allow the flame deflector protection system to safely meet the requirements of diverting the flames, exhaust, and other small items loosened during a launch away from the launch complex and vehicle, will preserve structure integrity of the launch complex, lower construction and repair costs, reduce high failure rates, and increase safety. The new material must exhibit long-term resistance to the extremely corrosive Florida coastal environment and the launch environment – the highly corrosive SRB hydrochloric acid exhaust, extreme temperature fluctuations between SRB heat impingement and subsequent noise suppression water deluge, and SRB blast vibrations.

1.2 Objectives of the Study

The objective of the Exploration Technology Development Program (ETDP) project, *Refractory Materials for Flame Deflector Protection System Corrosion Control,* is to develop replacement refractory materials that exhibit long-term resistance to degradation. Knowledge gained from the development of refractory material systems for flame deflectors will be leveraged to evaluate materials and systems for the replacement of refractory fire bricks along the flame trench vertical walls. The flame deflector must safely divert flames, exhaust, and small items that are loosened during a launch. In essence, the system must prevent debris from bouncing back and hitting the launch complex and vehicle. Performance in this regard is dependent upon integrity of the refractory materials used on the flame deflectors.

A sustainable program hinges on how effectively total life cycle costs are managed. Developmental costs are a key consideration, but total life cycle costs related to the production, processing, and operation of the entire architecture must be accounted for in design decisions to ensure future resources are available for ever more ambitious missions into the solar system. Historical data shows that typically life cycle costs of a program are set within the first 10% of its life and that design solutions (to problems encountered during development) often are not adequately scrutinized for their potential impacts on Ground and/or Mission operations impacts over the remaining balance of the program.

The objective of this sub-element task is to perform a life cycle cost (LCC) analysis that compares the operational life cycle costs, processing/turnaround timelines, and operations manpower inspection/ repair/ refurbishment requirements for corrosion protection of KSC Launch Pad Flame Deflector associated with the existing cast-in-place materials and a newer advanced refractory ceramic material. The LCC analysis for the launch pads includes costs associated with all damage and potential damage resulting from refractory foreign object debris, the costs for repairing the refractory concrete in the flame deflectors, the damage resulting to the steel base structure caused by refractory concrete cracking or failure, planning and engineering costs associated with the flame deflector repair, and other potential costs. It is anticipated that advanced refractory materials would provide corrosion protection of critical program operational assets which reduces life cycle cost by reducing corrosion failures, decreasing the need for maintenance, and minimizing the environmental impact of corrosion protection.

This report describes the assets analyzed for the life cycle cost analysis, the damage and failures that occur to these assets, quantifies the damage, assigns costs to the damage, and performs an economic analysis to assess the feasibility of the proposed research. It should be noted that the feasibility study has been performed taking a long-term perspective that considers the overall life-cycle of the protection system and launch complex.

In the current study, the flame deflector system is defined as a set of structures and materials that are used to protect the Space Shuttles and GSE from the flames and exhaust produced by the SSMEs and SRBs. This system includes the flame deflector and flame trench (walls and floors). This economic study compares the economic benefits of implementing a new ceramic lining material into the flame deflector system at Launch Complex 39A (LC 39A) and Launch Complex 39B (LC 39B).

The feasibility will be assessed by identifying the damage that occurs during launches, associating costs with this damage, quantifying the costs, and then performing a life-cycle cost analysis to assess the value of performing such research. Alternatively, if the analysis shows that potential economic benefits do not meet NASA requirements, a recommendation will be made to not pursue the research.

1.3 Corrosion of the KSC Launch Environment

The launch facilities at KSC are approximately 1,000 feet from the Atlantic Ocean. The seacoast marine location is extremely corrosive to structural steel. In fact, the beachside location at KSC is documented as one of the most corrosive environments in the world. Table 1 shows the corrosion rates for the KSC Beachside Atmospheric Exposure Test Site. The corrosion rates in the table clearly show the aggressiveness of the KSC locale, in relation to the others that are listed.

KSC launch facilities and GSE are exposed to extremely corrosive marine conditions. As if those natural conditions were not bad enough, in 1981, the Space Shuttle introduced a more aggressive environment to the launch pads at KSC. Exhaust from the SRBs resulted in the deposition of small alumina (Al_2O_3) particles with hydrochloric acid adsorbed onto their surface. It is estimated that 70 tons of hydrochloric acid are generated during a Space Shuttle launch. The impingement of this acidic exhaust results in the failure of refractory materials, despite the fact that a pressure wash-down is performed immediately after launch.

Table 1. Corrosion Rates of Carbon Steel Calibrating Specimens at Various Locations[1]

Location	Type of Environment	µm/yr	mils/yr
Esquimalt, Vancouver Island, BC, Canada	Rural marine	13	0.5
Pittsburgh, PA	Industrial	30	1.2
Cleveland, OH	Industrial	38	1.5
Limon Bay, Panama	Tropical marine	61	2.4
East Chicago, IL	Industrial	84	3.3
Brazos River, TX	Industrial marine	94	3.7
Daytona Beach, FL	Marine	295	11.6
Pont Reyes, CA	Marine	500	19.7
Kure Beach, NC (24 m from ocean)	Marine	533	21
Galeta Point Beach, Panama	Marine	686	27
Kennedy Space Center, FL (Beach)	**Marine**	**1070**	**42**

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[1] S. Coburn (1978), "Atmospheric Corrosion," in *American Society for Metals, Metals Handbook, Properties and Selection, Carbon Steels,* Metals Park, Ohio, 9th ed., Vol. 1, p.720.

In response to the SRB exhaust problem, studies were conducted at KSC to increase the chemical resistance of protective coatings and materials in response to this more aggressive propulsion system.[2,3,4,5,6,7,8] Because of these studies, the NASA Coatings Standard, NASA-STD-5008, *Protective Coating of Carbon Steel, Stainless Steel, and Aluminum on Launch Structures, Facilities, and Ground Support Equipment,* was revised to incorporate additional zones of exposure with coating requirements for surfaces that receive acid deposition from SRB exhaust products.

2 FLAME DEFLECTOR SYSTEM

The flame deflector systems at LC 39A and LC 39B are critical to protect NASA assets that include the Space Shuttle, GSE, and personnel. As the name implies, the system diverts rocket exhaust away from critical structures through its geometric design. Further benefits are provided by a water deluge system that dampens acoustic vibrations and high temperatures associated with launches.

Flame deflectors are typically covered with a heat resistive material that protects the flame deflector from erosion, ablation, and extreme temperatures that are produced by the rocket propulsion systems. If this refractory layer is compromised, deterioration to the flame deflector and other load bearing structures may result. Once compromised, the refractory material and flame deflector substructures can turn into unwanted projectiles known as FOD that can cause consequent damage.

2.1 Main Flame Deflector and Flame Trench

LC 39A and 39B were originally designed to support the Apollo Program. With the advent of the Shuttle Program, the Saturn era flame deflectors were replaced. Figure 2 shows a schematic cross section of the flame deflector at LC 39A. The flame deflector system consists of a flame trench, a main flame deflector (MFD), and a pair of side flame deflectors (SFD). The main flame deflector is designed in an in inverted, V-shaped configuration, is constructed from structural

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[2] D. Ruggieri and Anne Rowe, Evaluation of Carbon Steel, Aluminum Alloy, and Stainless Steel Protective Coating Systems After 18 Months of Seacoast Exposure, NASA Technical Memorandum 103503, May 1984.

[3] L.G. MacDowell, Evaluation of Protective Coating Systems for Carbon Steel Exposed to Simulated SRB Effluent after 18 months of Seacoast Exposure, NASA Report No. MTB-268-86B, February 1988.

[4] L.G. MacDowell, Volatile Organic Content (VOC) Compliant Coating Systems for Carbon Steel Exposed to the STS Launch Environment – Application, Laboratory and 18 Month Exposure Results, NASA Report No. FAM-93-2004, February 23, 1993.

[5] L.G. MacDowell, Testing VOC-Compliant Coating Systems at Kennedy Space Center, Materials Performance, 32, p. 26–33 (1993).

[6] L.M. Calle and L.G. MacDowell, Improved Accelerated corrosion Testing of Zinc-Rich Primers, NASA Tech Briefs, 24, p. 78, (2000).

[7] L.M. Calle and L.G. MacDowell, Evaluation of Inorganic Zinc-Rich Primers Using Electrochemical Impedance Spectroscopy (EIS) in Combination with Atmospheric Exposure, in proceedings of NACE International Conference on Corrosion in Natural and Industrial Environments: Problems and Solutions, May 23–25, 1995, Grado (Gorizia), Italy.

[8] L.M. Calle and L.G. MacDowell, Evaluation of Inorganic Zinc-Rich Primers Using Electrochemical Impedance Spectroscopy (EIS) in Combination with Atmospheric Exposure, NASA Report No. 94-2082, John F. Kennedy Space Center Florida, April 17, 1995.

steel, and is covered with refractory concrete material. One side of the inverted "V" deflects the flames and exhaust from the SSME and the opposite side deflects the flames and exhaust from the SRBs. Additional protection is provided by a "secondary system," which consists of two movable side deflectors at the top of the trench that provides additional protection from SRB exhaust. The orbiter side of the new flame deflectors is 38 ft high, 72 ft long and 57 ft wide. The SRB side of the flame deflector is 42 ft high, 42 ft long and 57 ft wide. The total mass of the asset is over 1 million pounds.[9]

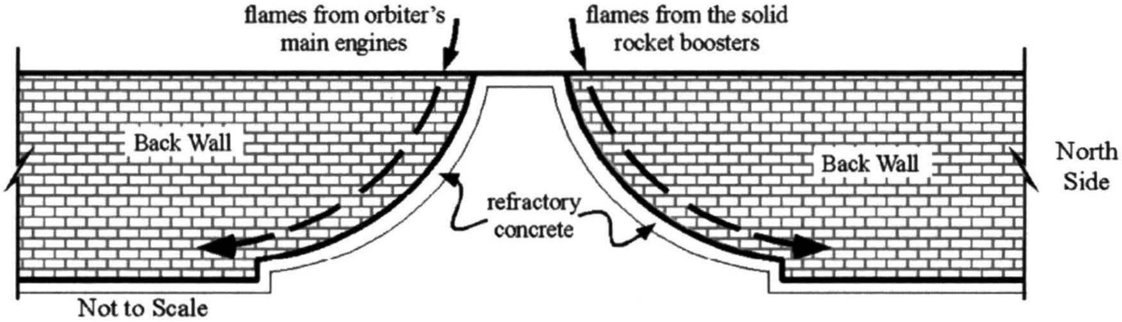

Figure 2. Cross Section of Flame Deflector at LC 39A

The flames from the main engines and the SRBs are channeled down opposite sides of the flame deflector. The deflector is constructed of steel on a structural steel I-beam framework. To protect the structure from serious degradation during launch, the faces of the flame deflector are lined with refractory concrete. This product is known as Fondu Fyre WA-1G supplied by the Pryor Giggey Co. The thickness of the refractory concrete is 6 inches on the SRB side, 4.5 inches on the SSME side, and 4 inches on the side deflectors.

Figure 3 shows the configuration of the Shuttle viewed upward from the flame trench. The openings for the Space Shuttle exhaust and the flame deflector used to divert the rocket plume from the SRBs are labeled. The other side of the flame deflector, which is not visible in the picture, diverts the exhaust from the main engines. The SRBs burn at approximately 3,000 °C, while that of the exhaust from the Shuttle main engines is considerably lower. Consequently, the higher temperatures of the SRB exhaust lead to more severe exposure conditions and result in damage that is more significant to the deflector.

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[9] Launch Complex 39A and 39B, http://science.ksc.nasa.gov/facilities/lc39a.html, (Last accessed December 17, 2008.

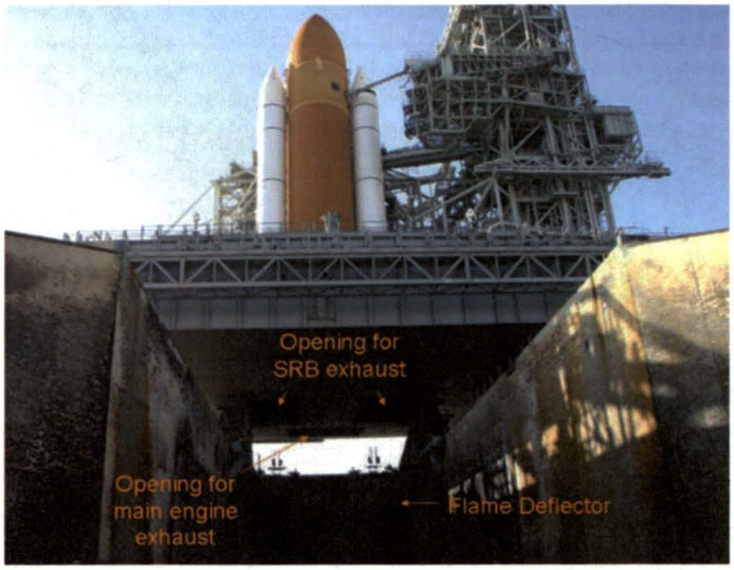

Figure 3. Openings for Flames from the Main Engine and SRBs

Figure 4 shows a magnified view of the flame deflector underneath the SRBs. The image shows the structural steel at the bottom of the deflector which is protected with Fondu Fyre. Figure 5 shows the SSME flame trench and deflector.

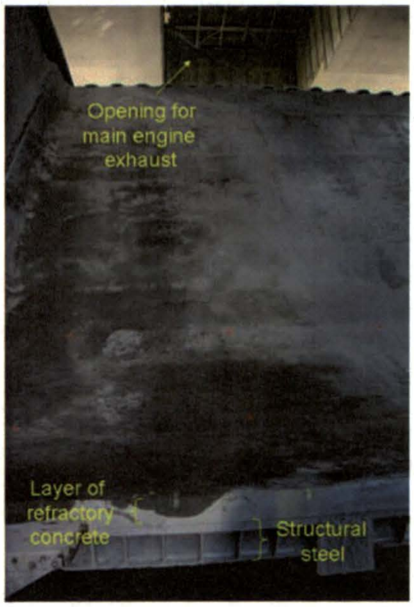

Figure 4. Magnified View of LC 39A Flame Deflector

Figure 5. SSME Flame Trench

Safely meeting the flame deflector requirements of diverting the flame, exhaust, and small items that are dislodged during launch, is dependent on the integrity and performance of the materials used to construct the flame deflectors. The use of refractory products that have superior material characteristics (under launch conditions) is necessary to protect the flame deflector, Space Shuttle, GSE, and launch personnel.

3 DETERIORATION AND REPAIR OF LAUNCH COMPLEXES

The launch complexes at KSC are critical support facilities that are required for the successful launch of space based vehicles. Most of these facilities are over 40 years old, and consequently, are experiencing deterioration. As a result of the constant deterioration from launch heat/blast effects and environmental exposure, the refractory materials used at LC 39A and LC 39B have become susceptible to failure, resulting in large sections of refractory material breaking away from the base structure and creating high-speed projectiles during launch. These projectiles jeopardize the safety of the launch complex, crew, and vehicle. Postlaunch inspections have revealed that the number and frequency of repairs, as well as the area and size of the damage, is increasing with the number of launches.

3.1 Observed Failures in the Launch Complexes

Spalled and dislodged refractory concrete, and firebrick that is missing from the walls of the flame trench, are anomalies that are routinely observed after a launch. Examples of these "typical" problems were witnessed and recorded on a walkdown of LC 39A after the launch of STS-126 (November 14, 2008).

Typically, spalled regions are more prevalent on the SRB side of the flame trench where the corrosive conditions are exaggerated by the acidic exhaust and airborne particulate matter of these motors. After the launch of STS-126, a similar spalled and dislodged region was found on the SSME side of the flame deflector (Figure 6). This section of refractory concrete was located halfway down the length of the flame trench. A picture of the dislocated concrete section is shown in Figure 7.

Figure 6. STS-126 Spalled and Dislodged Concrete Section

Figure 7. Section of Refractory Concrete Dislodged During the Launch of STS-126

This anomaly may have resulted from the seepage of water through the cracked refractory concrete. It is possible that corrosion of the grid steel reduced the adhesion between the refractory and base material. During launch, the water under the concrete section may have turned to steam, lifting the section from the surface.

Firebrick that has been dislodged from the walls of the flame trench is another anomaly that is frequently seen after a Shuttle launch. An example of this phenomenon witnessed on the SRB side of the LC 39A flame deflector after STS-126 is shown in Figure 8

Figure 8. Missing Refractory Brick at LC 39A

A non-typical example of flame trench degradation occurred during the launch of STS-124 on May 31, 2008 when serious damage to the east walls of the flame trench occurred during the launch of the Space Shuttle Discovery. Blast from the SRBs resulted in the expulsion of around 3,540 firebricks (16 percent of the wall) from the flame trench walls (Figure 9). The interlocking firebricks were attached to the 3 foot thick concrete substructure with epoxy and dove-tail metal clips. The metal clips, attached to slotted channel embedded in concrete, are installed horizontally to every other brick, and vertically at every sixth row.[10]

Figure 9. Extensive Dislocation of Firebrick on May 31, 2008

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[10] Spaceflight Now | STS-124 Shuttle Report, http://spaceflightnow.com/shuttle/sts124/080612pad/index.html **(Last** accessed January 14, 2009).

These sections of refractory brick were ejected downrange from the launch site and beyond the perimeter fence at LC 39A. The total distance traveled by some of the firebrick was over 1,500 feet.[11] Figure 10 [12] and Figure 11 [13] show the extent of FOD that was produced by the bricks that were torn away from the flame trench walls.

Figure 10. Refractory Concrete Bricks Torn Away From the Flame Trench

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[11] Interview with John Lane; ASRC Aerospace Corporation; January 14, 2009.

[12] http://www.usatoday.com/tech/science/space/2008-06-27-nasa-launch-pad-repairs_N.htm.

[13] http://www.collectspace.com/ubb/Forum30/HTML/000701-2.html **(Last accessed January 26, 2009).**

Figure 11. Refractory Concrete Bricks Around Fences

While this example of extensive destruction of refractory structures is not the norm, the cost associated with its repair was very high (estimated at 2.7 million U.S. dollars). Ultimately, the firebrick was replaced with Fondu Fyre refractory concrete that was gunned in place.

3.2 Classification of Repair Activities

Repair and maintenance activities are classified according to the following flame deflector areas:

- The steel base frame of the MFD. The steel base frame was constructed using conventional carbon steel.
- The refractory concrete exposed to the SRB and SSME exhaust impingement on the exterior of the MFD and SFDs.
- The walls and floor of the flame trench, which is concrete that is lined with refractory firebrick.

For the analysis in this report, repairs are categorized into minor and major classifications. Minor repairs are performed by in-house personnel, while the more extensive and costly major repairs are performed by outside contractors. The differentiation between minor and major repairs depends on

- time constraints,
- the size of the repair,
- availability of personnel resources and installation equipment (casting vs. gunning), and
- FOD induced security issues that result from damage to perimeter fences and constraints.

3.3 Evaluation of Repair Needs

Inspections are usually performed by visual and mechanical nondestructive sounding methods. The repair requirements are dependent upon size, location, extent of fractures and cracks in the refractory concrete cover, and the extent of missing sections or pieces of refractory concrete. The desired condition of the post launch refractory concrete protection system requires that there are no spalls or missing pieces of refractory concrete cover and cracking of the refractory concrete cover material that is characterized as being no more than 1/8 inch wide, 12 inches long, and 1 inch deep. Often, cracking can be found in areas adjacent to the loosened concrete. If the dimensions of the cracks fall outside these parameters, remediation of these areas is required per Maximo job plan #27354.[14]

3.3.1 Steel Structure of Main Flame Deflector

Corrosion of the base steel structure is dependent on the condition of the refractory material. The refractory material acts as a barrier to the aggressive Florida coastal environment (i.e., high humidity and chloride exposure). Typically, a sound and uncracked refractory concrete cover will prevent corrosion to the base structure, much better than a fractured and cracked layer of protection. During launch, hydrochloric acid is produced by the SRBs and is deposited on the flame deflector surface. This solution is extremely corrosive to the structural steel base structure. A fractured and cracked refractory coating will allow the hydrochloric acid to permeate through to the base structure, thereby accelerating its corrosion.

The flame deflector's structural steel is routinely inspected for corrosion. After inspection, a decision is made as to what corrective action is needed. Minor repairs are performed when only loose rust and/or corrosion debris is present. Typically, these repairs do not require sandblasting and are performed by in-house personnel. Major repairs are performed for more severe corrosion conditions. These repairs typically require sandblasting and are performed by outside contractors.

3.3.2 Refractory Concrete

The flame deflector is coated with a refractory concrete material (Fondu Fyre); while the walls and floor of the flame trench have historically used refractory brick for thermal protection.

Once compromised, the general methodology used to repair the refractory concrete surface includes

- removing loose or damaged refractory concrete sections by cutting or hydro-blasting unwanted material (Figure 12),
- welding and repairing grid steel or Nelson studs to the base steel, and
- casting or gunning refractory concrete in place.

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[14] E-mail correspondence with Chris Parlier; NASA Structural Engineering; January 29, 2009.

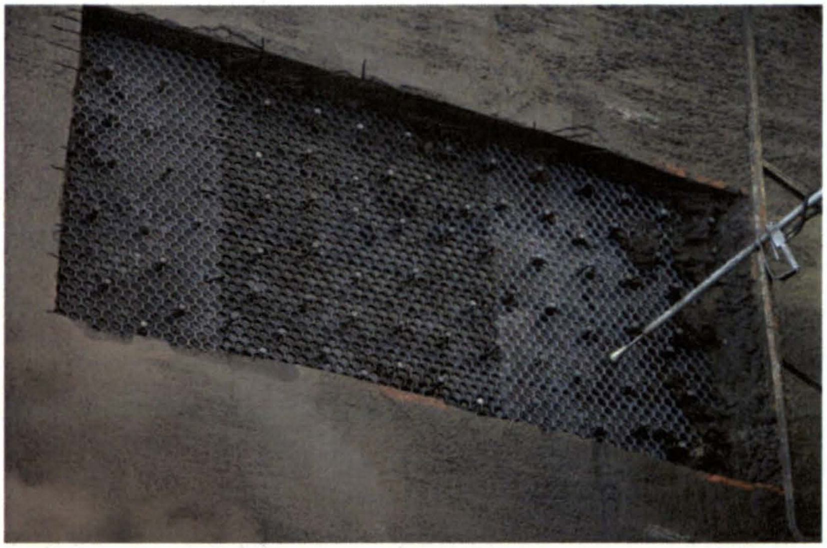

Figure 12. Cut-Out Section of a Refractory Material on LC 39A Repair, Showing the Underlying Grid Steel Honeycomb Structure With Steel Nelson Studs Protruding Outward

When the amount of refractory damage is too large for efficient removal and replacement by in-house personnel, a fixed price contract is generated so outside contractors can perform the prior outlined procedures.

3.3.3 Repair of the Refractory Bricks on Trench Walls

The refractory materials that line the flame trench dislodge on a fairly regular basis due to the extreme conditions generated by the Space Shuttle's propulsion system.

Various factors prevent the replacement of refractory firebrick with a "like product." Foremost is the unavailability of product. A.P. Green, the original supplier, no longer manufactures it. The product dimensions and material formulation are unique to NASA. Furthermore, the dry-set tongue and groove design, as well as the methodology to secure the bricks to the flame trench walls, makes single brick replacement difficult and cost-prohibitive. Consequently, when firebrick is lost from the flame trench walls, repairs are made by replacing the bricks with gunned Fondu Fyre WA-1G.

4 INPUT AND DATA ANALYSES

This chapter discusses the methodology used to generate input data necessary to conduct the economic analysis. Analyses were performed using repair cost data and frequencies, Shuttle launch frequency and a history of damage to the refractory concrete.[15] This record was cross-referenced with archived damage assessment data that was provided by United Space Alliance (USA) personnel.[16]

4.1 Repair Costs and Frequency Data

Repair frequencies and costs for refractory repair and refurbishment were collected. Each individual data set provided insight into refractory degradation associated with individual components of the entire flame deflector system. These components (along with costs) are delineated in Table 2.

Table 2. Repair Frequencies and Costs

Area	Material Type	Repair Type	Frequency	Average Cost per Repair	Project Duration
Steel Structure of the Main Flame Deflector	Carbon Steel	Minor	Postlaunch	$16K	2 weeks
		Major	Annually	$400K	3 weeks

The term *refractory concrete coating* refers to maintenance and repair of refractory concrete materials used to protect the surface of the flame deflector. *Steel structure of the main flame deflector* refers to the carbon steel framework that comprises the structural skeleton of the flame deflector. Finally, the term *flame trench* is used to refer to sections away from the flame deflector that are protected by refractory materials. These areas include the flame duct walls and floor that is protected by refractory firebrick.

Corrosion cost estimates were collected from NASA and USA engineering personnel during a technical interchange. The combined data was required to successfully determine the frequency of repair and the costs for the individually classified flame deflector components.[17]

4.1.1 Average Repair Frequencies and Costs

Table 2 shows average repair frequencies and the costs as a function of each component of the flame deflector. These reported values were obtained from questionnaires distributed to NASA and contractor personnel. The objective of the questionnaires was to identify cost information that may not be identified during this investigation. The questionnaire proved useful by providing a measure of "reasonableness" for the documented data.

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[15] Engineering Review Board (2008), "Fondu Fyre Historical Liberation" (Action Response for Debris Integration Group), NASA Kennedy Space Center, Florida.

[16] NASA Refractory Concrete Technical Interchange, August 13, 2008.

[17] NASA Refractory Concrete Technical Interchange, August 13, 2008.

As shown in Table 2, for the steel structure of the main flame deflector, the average estimated costs of minor and major repairs are approximately $16K and $400K, respectively. Minor repairs occur after every Shuttle launch and major repairs occur annually. These costs and frequencies cover launch complexes 39A and 39B. Also, the costs represent direct repair costs, which do not include contractors' markups and NASA's oversight. The repair activities are classified as minor and major as previously described in Section 3.

Because of the limited availability of refractory firebrick for NASA's applications and as a result of the steep labor costs associated with its installation, Fondu Fyre refractory concrete is the preferred material for repairs. Consequently, activities used to repair refractory concrete on the face of the flame deflector are similar to those used to repair flame trench walls.

4.1.2 Detailed Structural Steel Costs for the Flame Deflectors

Costs associated with the flame deflector's structural steel were obtained from United Space Alliance (USA). The data included FY 2003 through FY 2008, and is summarized in Table 3. Clearly, the costs associated with structural steel repair of the flame deflectors are quite large. As the historical data for the past six years indicates, the average expenditure for contracted repairs (major efforts) associated with the structural steel is quite large.

Table 3. Repair Costs for the Main Flame Deflector Steel Structure

FY	Launch Complexes	Costs
2003 & 2004	39 A	NA
	39 B	$243,142
2005	39 A	$511,231
	39 B	$271,814
2006	39 A	$2,696,425
	39 B	$235,917
2007	39 A	$473,161
	39 B	$201,027
2008	39 A	NA
	39 B	$430,672
Sum		$5,063,389
Annual Cost		$421,949

A significant refurbishment effort of the flame deflector structural steel at LC 39A occurred in 2006. Interviews with NASA and USA launch personnel indicated that the complete refurbishment of the flame deflector structural steel occurs every ten years (on average).[18]

4.1.3 Yearly Flame Duct Repair Costs for Structural Steel

For both launch complexes, the overall average repair cost for the steel structure was determined by considering the different types of repairs: minor and major repairs (shown in Table 2) and major rehabilitation costs (the cost from LC 39A during FY 2006 shown in Table 3). The

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[18] NASA Refractory Concrete Technical Interchange, August 13, 2008.

rehabilitation cost was rounded to $2.7M since an exact number from the table implies a high accuracy for future estimates.

Table 4 provides the estimated average annual repair costs for the steel structure, and the average (minor) repair costs per Shuttle launch. In Table 4, the minor and major repair costs (of the steel structure) are $16K and $400K, respectively.

Table 4. Estimation of Annual Average Repair Costs for Steel Structure

Type of Repairs	Average Costs	Repair Frequency	Annual Costs (Direct Costs)
Minor	$16,000	Postlaunch (4.4 Launches per Year)	$70,400
Major	$400,000	Annually	$400,000
Major Rehabilitation	$2,700,000	10 Years	$270,000
Average Cost/Year			$740,400
Average Cost per Shuttle Launch	(4.4 Launches per Year)		$168,273

The minor costs were extrapolated to an annual figure, using the assumption that 4.4 Shuttle launches occur per year (there have been total 124 Shuttle launches during the last 28 years). Major costs were reported as an annual figure, and are summarized as such in Table 4.

Costs associated with the major rehabilitation of the structural steel were amortized over the anticipated life of the structure. For the rehabilitation effort in 2006 allocates $270,000 of the cost given a 10-year frequency of rehabilitation.

Based on the estimates in Table 4, the average annual cost for the flame deflector structural steel is approximately $740K. This results in an average cost of $168K for each Shuttle launch, and assumes 4.4 Shuttle launches occur each year. This figure will be used as a pertinent variable in the life cycle analysis section of this report.

It is important to note that the repair costs (reported in this section) do not include contractor markup and NASA oversight. Again, referenced estimates are used in the life cycle analysis section of this report.

4.2 Frequency of Shuttle Launches

The materials used to repair the refractory concrete lining and the flame trench is the same (Fondu Fyre WA-1G). As a result, the repair activities for the flame deflector and trench can be simultaneously analyzed.

As shown in Table 4, on average, a minor repair of the refractory concrete lining costs approximately $16K and is required after every Shuttle launch (not to be confused with the $16K repair costs of the steel structure). A major repair for the refractory lining costs approximately $300K and is assumed to occur annually.

For the flame trench (not the deflector), the average costs of the minor and major repairs were assumed to be $16K and $400K, respectively. Minor repairs are assumed to be performed after every Shuttle launch, while major repairs are required every 5 years. These costs represent direct repair costs, and do not include contractors' markups and NASA's oversight.

Table 5 shows a summary of the data collected from the questionnaires. After the data was collected, the research team found data related to quantities and costs associated with the repair of the refractory lining. Consequently, the questionnaire provided a method to check the reasonableness of the data. The following sections provide information related to the collection of data, and resulting estimates of repair costs.

Table 5. Frequencies and Costs for Refractory Concrete Lining Repairs

Area	Material Type	Repair Type	Frequency	Average Cost per Repair	Project Duration
Refractory Concrete Coating	Refractory Concrete (Fondu Fyre)	Minor	Postlaunch	$16K	2 weeks
		Major	Annually	$300K	3 weeks
Walls and Floors of the Flame Trench	Concrete Lined with Refractory Fire Bricks	Minor	Postlaunch	$6K	1 week
		Major	5 Years	$400K	3 weeks

4.3 Frequency of Shuttle Launches

Shuttle launches result in damage to the flame deflector systems. Repairs are typically performed when the damage is identified. Therefore, a correlation between the repairs as a function of Shuttle launches was investigated. To assess this possible relationship, the frequency of Shuttle launches was assessed.

Figure 13 shows the number of Shuttle launches that occurred as a function of each launch pad over the past 28 years.[19] Appendix A provides the tabulated data that was used to generate the figure.

There have been 124 Shuttle launches since the inception of the Space Shuttle Program. The first Shuttle launch occurred in 1981 from LC 39A. Among the 124 Shuttles, 71 (57%) were launched at LC 39A, and the remaining 53 (43%) were launched at LC 39B. The first Shuttle launch at LC 39B occurred in 1986. Obviously, LC 39A has been used more extensively, and over a longer period of time.

As shown in Figure 13, Space Shuttle launches increased in frequency from 1981 to 1986 while NASA ramped up operations. In 1986, the Challenger tragedy curtailed launches for an intermittent period of time. A similar halt to Shuttle missions occurred after the Columbia tragedy in February 2003.

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[19] Space Shuttle Mission Archive, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/list_main.html **(Last** accessed January 22, 2009).

Other than the initial increase (from 1981 to 1986), no other specific pattern in the number of launches per year is observed. However, the information on Shuttle launch frequency can be useful when it is combined with information related to the degradation caused by the Shuttle launches.

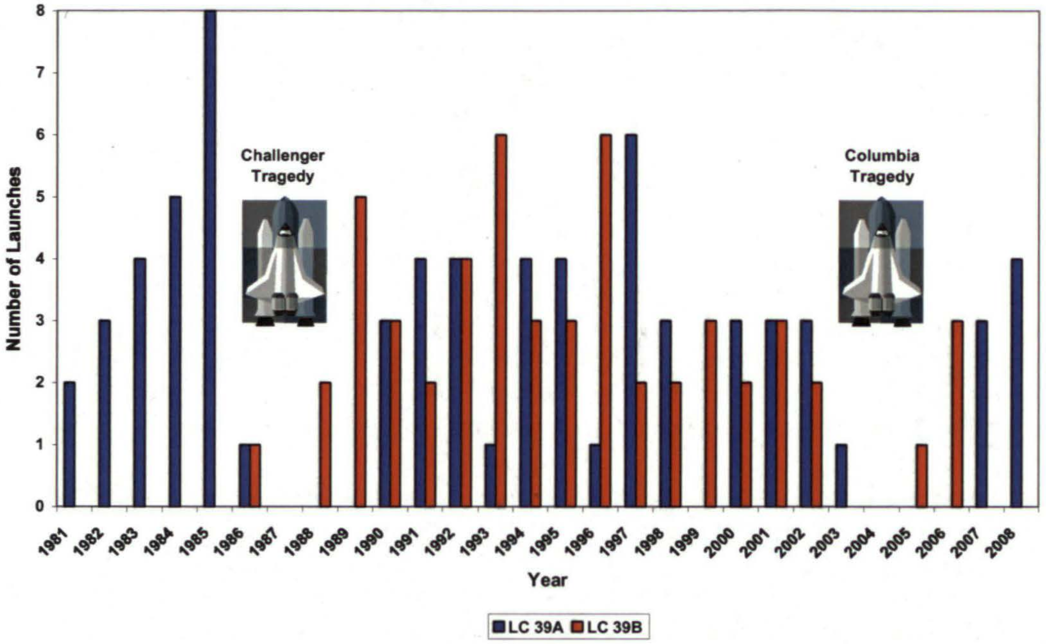

Figure 13. Space Shuttle Launches by Year and Complex From 1981 Through 2008

4.4 Repair Frequency Correlated to Shuttle Launches

NASA's Fondu Fyre damage history provides size measurements and descriptions of refractory damage that occurs from the Shuttle launches.[20] The document covers the damage to the flame deflector, as well as the walls and floors of the flame trench.

Quantitative size measurements were not available for all of the damage reports. However, the frequency of repair activities can be extracted from the data. The data is provided in Appendix B.

The frequency of repair was combined with the frequency of Shuttle launches to identify potential relationships. Figure 14 and Figure 15 are combinational analyses that show the number of Shuttle launches and repairs for LC 39A and 39B, respectively.

A comparison of the number of Shuttle launches with the number of launch pad repairs in Figure 14 and Figure 15 shows similar trends. The data indicates that the frequency of repairs, compared to the frequency of launches, are not well correlated for LC 39A from 1981 to 1987.

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[20] Engineering Review Board (2008), "Fondu Fyre Historical Liberation" (Action Response for Debris Integration Group), NASA Kennedy Space Center, Florida.

Limited correlation is also observed for launch and repair frequencies from 1986 to 1989 at LC 39B.

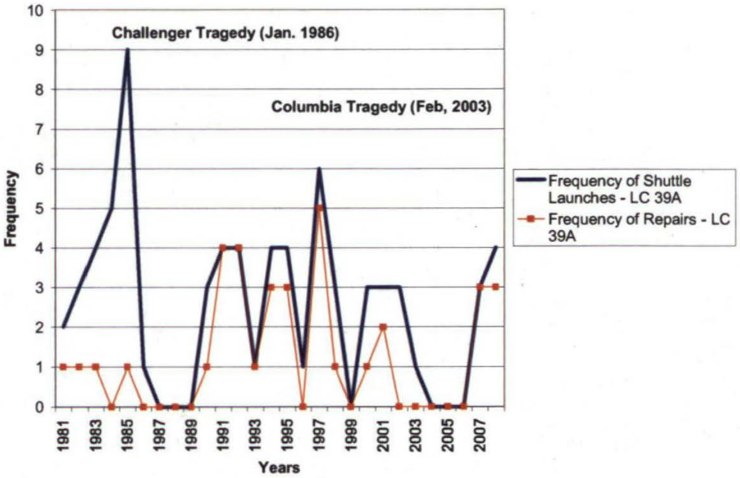

Figure 14. Frequencies of Shuttle Launches and Repairs – LC 39A

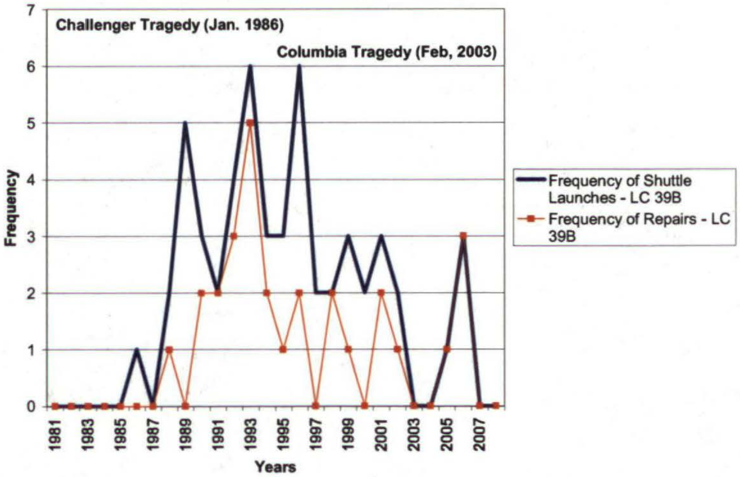

Figure 15. Frequencies of Shuttle Launches and Repairs – LC 39B

Since the first Shuttle launch at LC 39A occurred in 1981, and the first Shuttle launch occurred at LC 39B in 1986, latent effects from early launch exposure may be a pertinent factor in the cost analysis. This observation indicates that the initial performance of the flame deflector system may have exhibited some deterioration with each Shuttle launch, and cumulative effects resulted in later deterioration and costs.

To better evaluate these latent effects, Figure 16 and Figure 17 are provided to show the cumulative number of Shuttle launches and repairs for LC 39A and 39B, respectively. As already noted, the number of launches at each LC are different (71 at LC 39A and 53 at LC 39B).

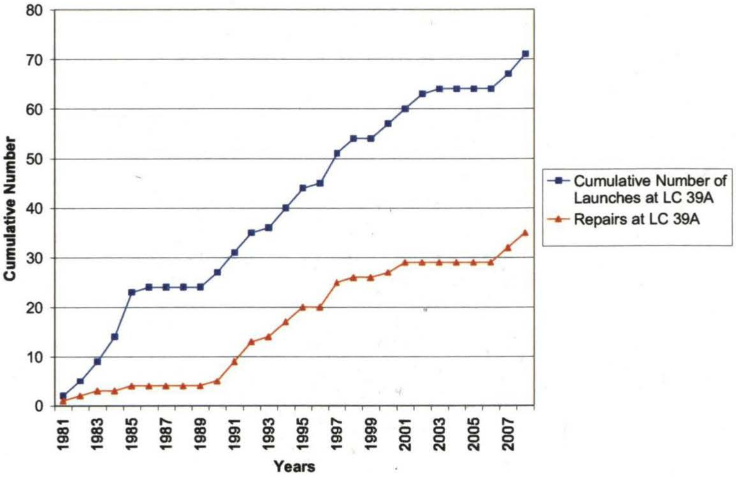

Figure 16. Cumulative Number of Repairs with Number of Launches – LC 39A

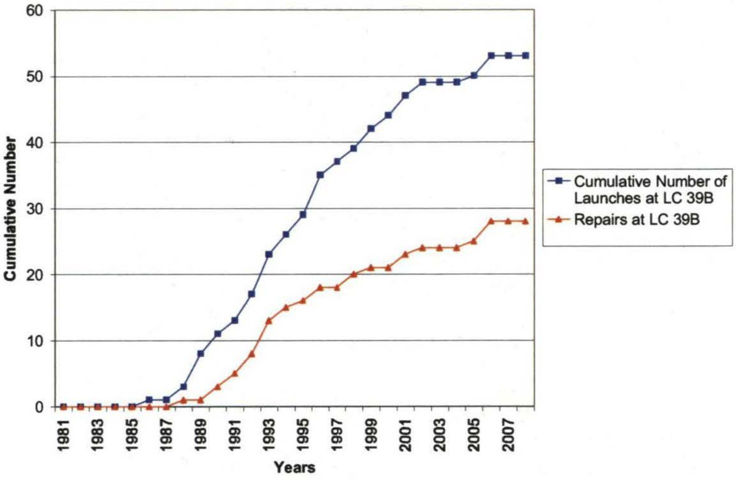

Figure 17. Cumulative Number of Repairs with Number of Launches – LC 39B

The latent effects are apparent from the cumulative repairs shown in Figure 16 and Figure 17. After the initial launch (and after the Challenger tragedy in 1986, parallel increases in the cumulative numbers of Shuttle launches and repairs were seen. The data for LC 39B (Figure 17) does not show this near parallel tracking. In general, it can be concluded that the extent of damage increases with increasing Shuttle launches.

4.5 Cumulative Repair Rate

The current analysis evaluates the launch/damage relationship by evaluating the cumulative repair rate. The cumulative repair rate is defined as follows:

$$\text{cumulative repair rate} = \frac{\text{cumulative number of repairs}}{\text{cumulative number of launches}} \qquad [1]$$

Figure 18 shows the estimated cumulative repair rate for both LC 39A and LC 39B over the past 28 years. The launch facilities had different cumulative repair rates early in each structure's use. However, over the years, the cumulative repair rates converged to a similar level at approximately 0.5. It should be noted that the rate of repair does not include the significance or extent of the damage, nor does it take into account the resulting repair costs. A repair after launch (counted as one repair in this analysis) may include multiple repairs of different components, such as the SRB MFD, the SSME MFD, the flame trench walls and/or floors, and/or the SFD.

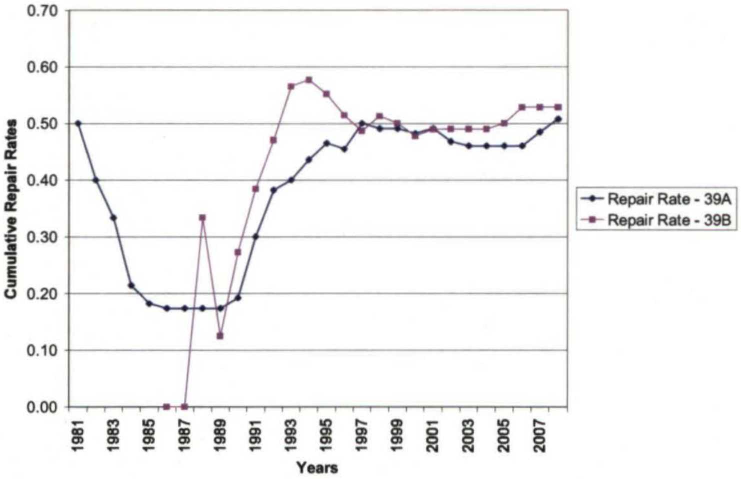

Figure 18. Cumulative Repair Rate

Note that the cumulative repair rate for the current year is actually the overall average for the last 28 years. In order to identify the transient trend in the repair rate, weighted moving averages were estimated (assuming a 5 year window).

Figure 19 shows the estimated moving averages. The moving average for the rate of repair peaked in the mid-1990s. According to NASA and USA personnel, major rehabilitation of the structures was performed in the 1992 to 1993 timeframe.[21] The most recently calculated moving average (of 1.0) indicates that NASA recently performed post launch repairs after every launch, which could be a result of structural deterioration of the flame deflector system.

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[21] NASA Refractory Concrete Technical Interchange, August 13, 2008.

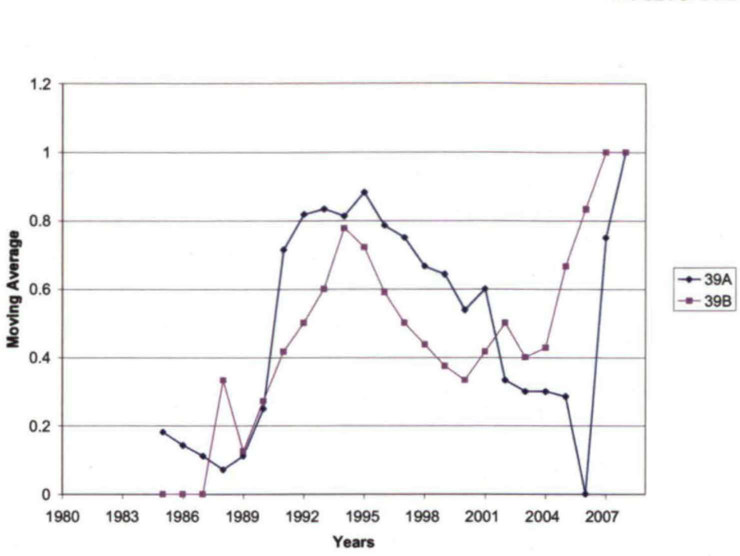

Figure 19. Moving Average of Repair Rates – 5 Year Window

4.6 Analyses of Fondu Fyre Damage History

The Fondu Fyre damage history provides qualitative descriptions of the refractory concrete damage, and a description of the degree of damage as a function of Shuttle launches.[22] The record covers Fondu Fyre damage on the main flame deflector, as well as damage to the trench walls and floors. The latter area is partially covered by a combination of refractory concrete bricks and Fondu Fyre refractory concrete.

A detailed analysis was performed using the Fondu Fyre damage histories since the data provides the most useful information amongst the available data sources. Unfortunately, information on the size of the damaged areas was not available for some of the reported data. The following sections provide a description of the approaches and assumptions used to overcome these limitations.

4.6.1 Mismatches Between the Dates of Damage and Launches

Damage to the Fondu Fyre is directly related to the number of Shuttle launches. According to the data, some damage was recorded several months after a Shuttle launch had occurred. Also, other launches had multiple damage records after a single launch. To clarify the relationship between damage and Shuttle launches, Assumption 1 is proposed.

> *Assumption 1: Repairs are made to all damage that occurs during a launch between the launch and the next flight from the same launch location. Therefore, damage and repair costs are attributed to the preceding Shuttle launch.*

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[22] Engineering Review Board (2008), "Fondu Fyre Historical Liberation" (Action Response for Debris Integration Group), NASA Kennedy Space Center, Florida.

Based on Assumption 1, all damage entries that are reported between two Shuttle launches are summed, and attributed to the previous Shuttle launch. Table 6 provides a summary of damaged areas and the dates of the previous Shuttle launches. There have been a total of 71 Shuttle launches at LC 39A. However, measurement of the size of the damage is only available for 16 Space Shuttle launches from LC 39A and 14 from LC 39B. The average sizes of the damaged areas at LC 39A and LC 39B (from data that includes size measurements related to damage) are approximately 392 and 188 sq. ft., respectively.

Table 6. Size of Damages with Shuttle Launches – LC 39A and LC 39B

	Launch Complex 39A		**Launch Complex 39B**	
No.	**Date of Launches**	**Size of Damages (Sq. ft.)**	**Date of Launches**	**Size of Damages (Sq. ft.)**
1	4/12/1981	41	1/28/1986	238
2	8/2/1991	1645	10/6/1990	375
3	9/12/1991	120	12/2/1990	720
4	11/24/1991	362	4/5/1991	225
5	1/22/1992	530	7/31/1992	30
6	3/24/1992	330	4/8/1993	55
7	4/26/1993	209	6/21/1993	50
8	2/3/1994	40	9/12/1993	70
9	7/8/1994	570	10/18/1993	100
10	3/2/1995	246	3/4/1994	355
11	2/11/1997	5	9/9/1994	245
12	7/1/1997	10	6/20/1996	90
13	8/7/1997	21	11/19/1997	9
14	9/25/1997	125	10/29/1998	75
15	1/22/1998	12		
16	5/31/2008	2000		
	Sum	6266	Sum	2637
	Average	391.6	Average	188.4

4.6.2 Unknown Size of Damaged Areas

Fondu Fyre damage was recorded for each of the different areas of the flame deflector system.[23] These areas include both the flame deflector and flame trench.

Table 7 and Table 8 show the total number of damages, the number of damaged areas with size measurements, the sum of the sizes of damaged areas, the average size of the damaged areas, and the number of damaged areas without size measurements. For the reported damage without size measurements, Assumption 2 is proposed:

> *Assumption 2: The average size of damaged areas for cases reported in the data will be used to estimate the size of the damaged areas for which size information is not available.*

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[23] Engineering Review Board (2008), "Fondu Fyre Historical Liberation" (Action Response for Debris Integration Group), NASA Kennedy Space Center, Florida.

Based on Assumption 2, which is commonly used to replace missing data in an analysis, the damaged areas without size information are assumed to be the same as the average size of the damaged areas for data with the recorded information. Consequently, the data in Table 7 and Table 8 were used to extrapolate the size of damaged areas for the records that did not have them listed.

Table 7. Damage Data for LC 39A

39A	**SRB MFD**	**SSME MFD**	**West SFD**	**East SFD**	**Trench Wall**	**Trench Floor**	**Wall Caps**
Number of Damages	27	13	7	6	9	5	3
Number of Damages with Actual Size Measurement	9	6	3	2	3	2	1
Sum (sq. ft.)	3173	666	34	72	2080	141	100
Average (sq. ft.)	352.6	111.0	11.3	36.0	693.3	70.5	100.0
Number of Damages without Size Measures	18	7	4	4	6	3	2

Table 8. Damage Data for LC 39B

39B	**SRB MFD**	**SSME MFD**	**West SFD**	**East SFD**	**Trench Wall**	**Trench Floor**	**Wall Caps**
Number of Damages	27	4	1	2	6	4	3
Number of Damages with Actual Size Measurement	12	1	1	2	3	1	2
Sum (sq. ft.)	1114	15	45	75	725	238	425
Average (sq. ft.)	92.8	15.0	45.0	37.5	241.7	238.0	212.5
Number of Damages without Size Measurement	15	3	0	0	3	3	1

4.6.3 Size of Repair Area vs. Size of Damaged Area

A recent failure of the flame trench walls at LC 39A resulted in a significant degree of damage. The Fondu Fyre damage records indicated that the size of the damaged was 2,000 sq. ft.[24] Once the project was complete, the actual size of the repair had grown to 4,500 sq. ft.[25] In general, the size of the repair will be greater than the size of the damaged area. Often, workers must follow

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[24] Engineering Review Board (2008), "Fondu Fyre Historical Liberation" (Action Response for Debris Integration Group), NASA Kennedy Space Center, Florida.

[25] **NASA approves Space Shuttle launch pad repair plan.** http://spaceflightnow.com/shuttle/sts124/080626paddamage **(Last accessed January 26, 2009).**

cracks in the refractory concrete, and cut fissured regions until a solid refractory matrix is encountered.

To adjust for the damage/repair ratio (i.e., from 2,000 sq. ft. to 4,500 sq. ft.), Assumption 3 was made.

Assumption 3: The area of the repair is 2.25 times the size of the damaged area.

4.6.4 Estimating Repair Quantities for Unreported Quantities

Based on Assumptions 1, 2, and 3, the raw data was completed to produce statistically useful figures. Using the completed data, the relationship between the damaged areas as a function of each Shuttle launch was determined. Figure 20 shows the damaged areas with the corresponding Shuttle launch dates. The markers in the figure (representing the size of damaged areas) show no trend, and appear to be randomly scattered. However, as found in Figure 14 through Figure 17, there are trends that correlate cumulative damage occurrences and cumulative launch activities. Therefore, cumulative measures were evaluated to identify possible patterns. Markers representing the size of damaged areas show no trend and seem to be randomly scattered. As a result of any identifiable pattern, cumulative cause and effect relationships were investigated.

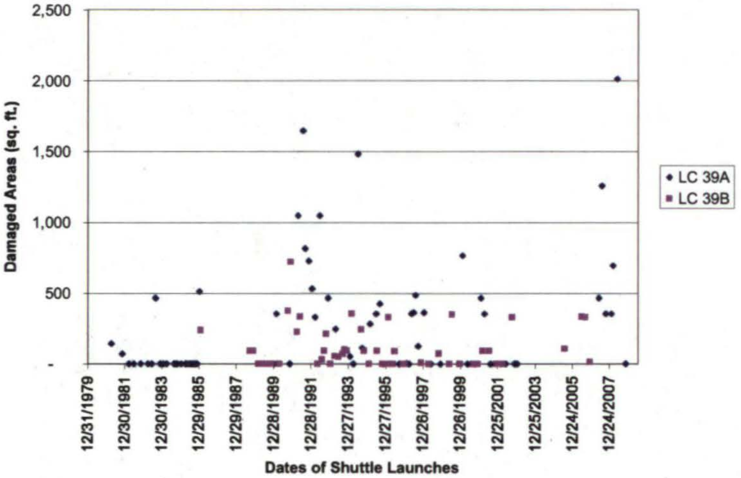

Figure 20. Damaged Areas with Dates of Shuttle Launches

Figure 21 and Figure 22 show the *cumulative damaged area* versus *cumulative number of launches* using the adjusted data for LC 39A and 39B, respectively. The cumulative sums of the damaged areas (in both figures) continually increase. This pattern would be expected to continue in the future. However, an analysis of the data indicates that, different trends are apparent for LC 39A and LC 39B. The mathematical analysis of the data for LC 39A indicates that the cumulative repairs (as a function of cumulative Shuttle launches) is a quadratic function with an R-squared of 0.93. In contrast, LC 39B exhibits a linear relationship with an R-squared value of 0.98.

Considering that degradation is a continuous process that affects structural materials with the increasing number of cumulative launches, the incremental size of damaged area is expected to increase. Therefore, the quadratic model for LC 39A is a reasonable forecast of the cumulative damaged area (as a function of the cumulative launches).

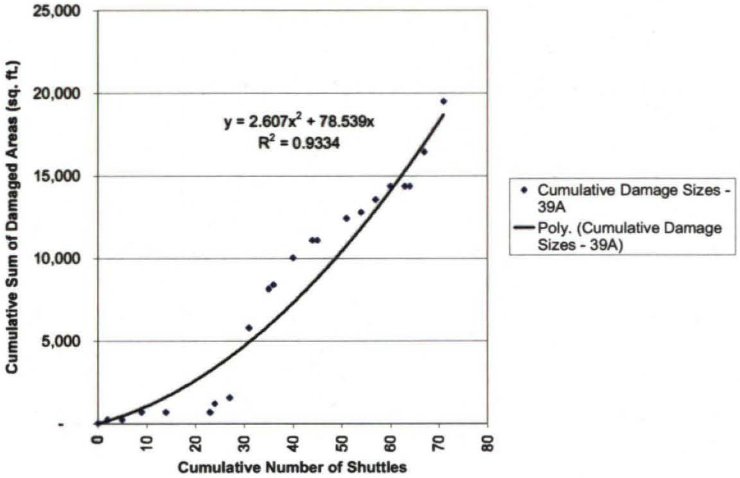

Figure 21. **Cumulative Damages vs. Cumulative No. of Launches – LC 39A**

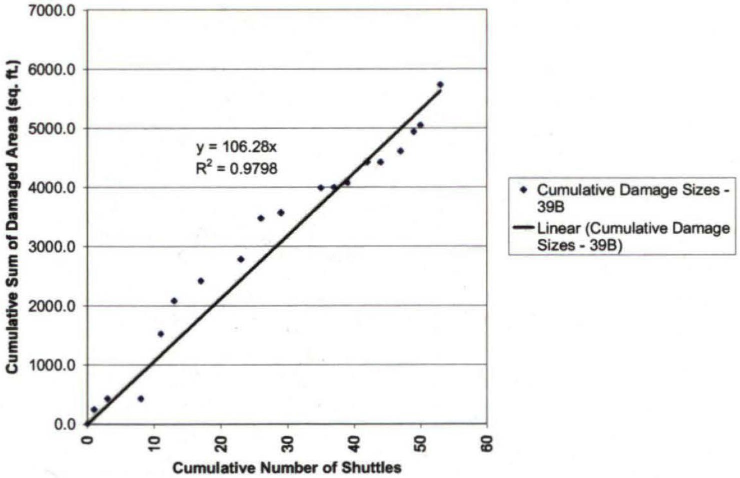

Figure 22. **Cumulative Damages vs. Cumulative No. of Launches – LC 39B**

The two equation models shown in Figure 21 and Figure 22 can be used to forecast the cumulative damage area of the refractory concrete as a function of the number of Shuttle launches. The closeness to 1 of the R-squared values signifies an excellent statistical fit of the data. Forecasted damage areas include all minor and major repairs, major replacements, and/or rehabilitations of the refractory concrete lining materials.

In comparison to the quadratic model in Figure 21, the linear model in Figure 22 can be considered conservative. Increases in cumulative area of damage are much more subdued as the number of Shuttle launches is increased with the linear model than with the quadratic model. Consequently, the research team chose the linear model to forecast cumulative damages. Doing so will reduce the likelihood that launch related costs would be overstated.

4.6.5 Unit Repair Cost per Square Foot

The average unit cost of a Fondu Fyre repair is approximately $200/sq. ft. if the repair does not require welding. When welding is required, the average unit cost is approximately $400/sq. ft.[26] Based upon the Fondu Fyre damage history,[27] there are a total of 33 records that indicate whether welding is required to make the repair. A summary of this data is shown in Table 9 and indicates that approximately 45.4% of the repair to the refractory concrete coating requires welding. Based upon this data set, Assumption 4 was formulated for the data analysis:

> *Assumption 4: On average, half of the damages will require welding. So, the average repair cost per sq. ft. of the damage area is $300/sq. ft. ($300/sq. ft = ($200/sq. ft. + $400/sq. ft.)/2).*

Table 9. Welding vs. No Welding

Launch Complex	Total Number of Records	With Welding	Without Welding	% Welding
39 A	17	8	9	47.1%
39 B	16	7	9	43.7%
Total	33	15	18	45.4%

4.6.6 Summary of Data Analyses on Fondu Fyre Damage History

As a result of the preceding data analysis related to refractory concrete repairs, the following methodology summarizes the requirements and assumptions for the refractory concrete cost analysis:

- The cumulative sum of damaged areas increases with the cumulative number of Shuttle launches according to the identified relationship in the following equations.
  - For Launch Complex 39A: $Y = 2.607\ x^2 + 78.539\, x$
  - For Launch Complex 39B: $Y = 106.28\, x$

  Y is the cumulative sum of damaged area
  x is the cumulative number of Shuttle launches.

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[26] NASA Refractory Concrete Technical Interchange, August 13, 2008.

[27] Engineering Review Board (2008), "Fondu Fyre Historical Liberation" (Action Response for Debris Integration Group), NASA Kennedy Space Center, Florida.

- The area of repair (as a function of initial damage estimate) is a factor of 2.25 times the initial estimate.
- The average repair cost for the refractory concrete is $300/sq. ft.
- The total repair costs include a markup factor of 1.25 for contractor markup, and an overhead factor of 1.05, which is attributable to NASA oversight.[28]

An analysis has been performed to determine the probability of damage (for each component of the flame deflector system) using the Fondu Fyre damage data[29] and the Space Shuttle launch history.[30] This analysis found that LC 39A and LC 39B have somewhat different flame deflector damage probabilities. In general, the flame deflector system at LC 39A has experienced more damage than LC 39B.

The highest probabilities of damage occurrences were related to the refractory concrete coating on the MFD. More significant damage was recorded for the SRB MFD, as compared to the SSME MFD. This relationship was exhibited at both launch complexes, and is as expected considering the higher temperatures, ablation, and acid content from the SRB exhaust. A detailed description of the analysis is provided in Appendix C.

4.7 Potential Safety Issues and Related Costs

Significant damage on the flame trench occurred when Discovery (STS-124) was launched from LC 39A on May 31, 2008. This incident resulted in the liberation of numerous refractory firebricks that were launched downrange. Any one of these foreign objects had the potential to cause significant damage to KSC's GSE and the Space Shuttle, thereby compromising the safety of launch personnel.

With the potential for such a large quantity of FOD to be ejected during a launch, safety must be considered as a disastrous and consequential effect. This study does not investigate the potential effects of FOD, and the astronomical costs associated with a Shuttle accident. Doing so would clearly leverage the data, and favor the development of new refractory materials. It is expected that construction of a new flame deflector that utilizes technologically advanced refractory materials will significantly reduce risks associated with FOD and significantly reduce costs associated with a catastrophic event.

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[28] NASA Refractory Concrete Technical Interchange, August 13, 2008.

[29] Engineering Review Board (2008), "Fondu Fyre Historical Liberation" (Action Response for Debris Integration Group), NASA Kennedy Space Center, Florida.

[30] Space Shuttle Mission Archive. http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/list_main.html **(Last** accessed January 22, 2009).

5 LIFE CYCLE COST ANALYSIS

The approach used to generate the economic analysis for the flame deflector at KSC's LC 39A and LC 39B is discussed here. This LCC analysis is an economic analysis tool that is used to compare the relative merit of competing project alternatives.[31] The basic steps for the analysis are similar in all cases. Using this approach, the following steps were used to conduct the LCC analysis.

a. Define the objective.
b. Generate alternatives.
d. Determine costs and benefits.
c. Formulate assumptions.
e. Compare costs and benefits and rank alternatives.

This process was used to evaluate the economic worth and relative merit of a technologically advanced refractory concrete; by analyzing initial costs, and discounted future costs such as yearly maintenance and refurbishment.

The first three assumptions were discussed in previous sections of this report. A more succinct discussion of the required assumptions will be discussed to present the analysis in a succinct manner.

5.1 Objective

This project considers the development of technologically advanced refractory materials for the launch pads at KSC. Current launches cause damage to the refractory protection system which is comprised of refractory concrete, firebrick, and a steel support structure.

Launch related damages require repairs on a routine basis, so that minimum program requirement levels are maintained for successive launches. When routine repairs are not economically feasible, the complete refurbishment of the structure (or components) can be considered as an alternative. Figure 23 depicts a typical life cycle process for a structure.

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[31] FHWA Interim Technical Bulletin "Life-Cycle Cost Analysis in Pavement Design," FHWA-SA-98-079, 1998.

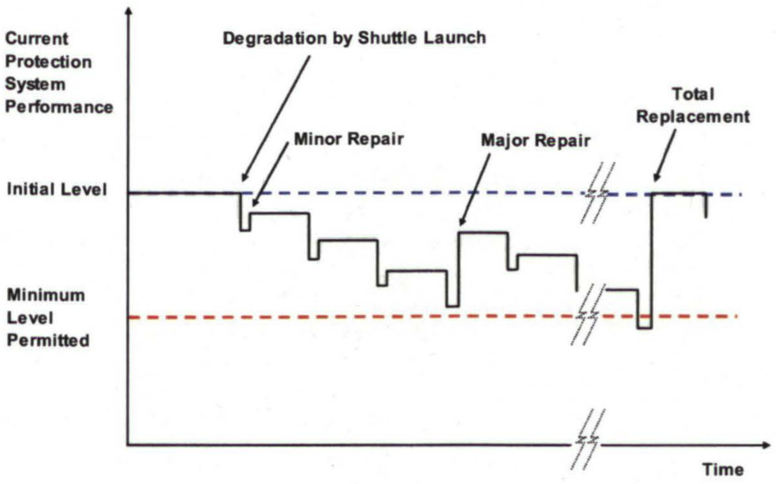

Figure 23. Life Cycle of the Structure

5.2 Alternatives for Analyses

The current economic analysis considers the following three repair scenarios:

- Alternative 1: Performing current repair practices without entire replacement;
- Alternative 2: Refurbishment of the entire flame trench using the current refractory concrete (Fondu Fyre); and
- Alternative 3: Refurbishment of the entire flame trench using technologically advanced refractory ceramics.

Alternative 1: Existing Practice

Alternative 1 assumes that the current flame deflector system will continue to be repaired following current practice. No major replacement of components or materials will be performed. This alternative assumes that the current trend, associated with increased damage from launch will continue, and current repair activities continue. In essence, the frequency of damage will continue to increase.

Alternative 2: Reconstruction with Existing Refractory Concrete

Alternative 2 assumes that NASA will reconstruct the entire flame deflector system and will use Fondu Fyre WA-1G as the refractory concrete coating. As a result, minimal repairs will be required from initial launch activities, but the extent of the damage and resulting costs will continue to current levels.

Alternative 3: Reconstruction with New Refractory Ceramic

Alternative 3 assumes that LC 39A and LC 39B will be constructed using technologically advanced refractory ceramic materials. It is expected that the new protection system will be resistant to fractures, cracks, and spalling. Additionally, it will provide superfluous wear characteristics, and at the same time, will be able to provide cost effective servicing after the initial installation. The major expectations of the new refractory ceramic protection system are:

- extended life-cycles,
- extended repair cycles, and
- 50% reduced costs associated with maintenance, and an increased lifespan that results in an overall savings of 75%.

5.3 Determination of Costs and Benefits

5.3.1 Routine Maintenance

Routine maintenance is performed through either USA Contracts or USA Standing Ground Operations. Therefore, the use of the technologically advanced ceramic material is expected to reduce USA Contracts and USA Standing Ground Operation costs. A reduction in contractor markup and NASA oversight will result from the integration of the technologically advanced ceramic materials.

5.3.2 Safety

Safety is of the utmost importance to all personnel. FOD is a top priority at the KSC launch complexes. All KSC employees are informed of this, routine messages are sent out to reinforce the importance of this issue, and specialized FOD training is provided as a requirement for area access in certain locations (including the launch pad areas). Loose objects are undesirable at the launch pads, but the FOD program requirements state that loose objects can be no larger than the size of a quarter or 0.016g in mass.[32]

Costs related to safety do exist, though the estimation of these costs is difficult and qualitative. FOD has been monitored during launch operations. It should be noted that the possible effects of FOD could be disastrous and extremely costly.

Due to the limited safety related data associated with the refractory concrete, the current study does not determine the costs related to these issues. However, the research team maintains that the replacement of the current refractory products, with those that are more technologically advanced, would significantly reduce FOD related threats during launch. By not including this variable, the analysis is considered to be conservative (i.e., the benefits are likely underestimated). Adding safety related costs to the analysis would have greatly favored the development of a new material.

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[32] NASA NE-M9 "KSC Corrosion Control Overview for Stennis Space Center," March 13, 2008.

5.3.3 Licensing

The developed technology can be used in other industries, even though it will be specifically developed for NASA. Often, technology development for NASA systems is carried out by NASA researchers, and is licensed to industry where it can be used by other industries. The development of a technologically advanced refractory system would have additional uses in industry and for other government agencies. The successful transfer of this technology to private industry is estimated to produce royalties.

There are many factors that come into play when determining royalties. The type of license (exclusive or nonexclusive), the strength of the patent, the state of the technology, competing technologies, and the amount of capital a company will have to invest to bring the technology to market, (etc.). As a result of these variables, a benefit (after licensing expenditures) associated with licensing was determined to be unquantifiable and was not included in this life cycle cost analysis.

5.3.4 Schedule

No Space Shuttle launch delays have been directly attributable to corrosion. While the possibility of launch delays due to the refractory system may exist, the probability of occurrence and associated costs were not deemed quantifiable as a part of this study.

5.3.5 Maintenance Costs Associated with the Advanced Refractory Concrete

The new refractory coating system is being formulated for use with ordinary methods of application. The new refractory is being designed so that it can be gunned in place. The ease of application associated with this method results in reduced labor costs associated with the maintenance of the refractory concrete products.

5.3.6 Product Availability

The current refractory concrete material, Fondu Fyre WA-1G, was developed solely for NASA, and is the only material available for use. However, it does not meet qualification requirements of the current specification, KSC-SPEC-P-0012 (April 25, 1979). Consequently, if the production of the material suddenly became unavailable, launch schedules will be jeopardized, and there will be increased costs associated with launch delays.

5.3.7 Summary of Costs and Benefits

Benefits associated with the refurbishment of the flame deflector (with technologically advanced ceramic materials) will include higher initial performance levels, reduced damage per Shuttle launch, lower frequencies of repair (longer repair cycles), and enhanced safety. Other potential benefits could include reduced material costs for labor and materials and licensing royalties.

The use of technologically advanced materials is intended to provide a more durable protection system for the steel base structure, which will be better able to retain its integrity under launch conditions. Consequently, the economic feasibility of developing and implementing new refractory materials is determined to assess the viability of developing advanced refractory materials for LC 39A and LC 39B.

5.4 Assumptions

The current economic cost model investigates the feasibility of developing a technologically advanced refractory system through a life cycle cost approach. To complete the analysis, the following assumptions were developed.

5.4.1 Period of Analysis

This forecast assumes a life cycle of 20 years, beginning in 2014, when the current research project is anticipated to be complete. The resulting savings to investment ratio (SIR) is therefore based upon this term.

5.4.2 Discount Rate

To assess the effects of the time value of money on the investments and relevant costs and savings, an interest rate is assumed to estimate the net present value. According to the government guideline[33] for economic analyses for federal investments, which is also referenced by the "KSC Cost Engineering Desk Reference,"[34] the current economic analysis used an annual interest rate of 2.7% for a 30-year forecast.

5.4.3 Number of Future Launches

Future Shuttle launches are only planned for the next two years. [35] According to the plan, 10 Shuttle launches will occur in that period. Based upon this plan, the current economic analysis assumes that there will be 5 Shuttle launches per year for this period. It is also assumed that NASA will (at least) continue this trend with future programs.

5.4.4 Treatment of Future Costs and Benefits

Repair costs and frequencies have been determined for LCC analysis, based on the data analyses performed using the actual data collected in this study. The analyses and assumptions were described in Section **Error! Reference source not found.**. Table 10 summarizes the variables used in the life cycle cost analysis. The reduction factor in Table 10 represents the reduction in the damaged area resulting from improved material performance (50%), as well as an increased benefit from the technologically advanced material (Alternative 3) lasting for longer durations.

The costs for reconstruction (using Fondu Fyre and the new refractory ceramic) are estimated, and the analysis is insensitive to these values. However, the analysis could be sensitive to the difference between these values—this will be evaluated later. The research team made general assumptions in quantifying these values. As a result, $1M was believed to be a reasonable, and likely the upper limit to implement this new material.

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[33] http://www.whitehouse.gov/omb/circulars/a094/a94_appx-c.html.

[34] Butts, G., "Cost Engineering Desk Reference (Draft)," 2006, p. 246, http://www.ksc.nasa.gov/nasa-only/finance/Cost_EST/index_files/Data/Estimating%20Desk%20Reference_109.pdf **(Last accessed April 9, 2008).**

[35] http://www.nasa.gov/missions/highlights/schedule.html.

Table 10. Variables Used in the Life Cycle Analysis

Variables		Values	Comments
Entire Replacement Costs Using Fondu Fyre		\$9,000,000	For Alternative 2
Entire Replacement Costs Using New Refractory Ceramic		\$10,000,000	For Alternative 3
Research Development Costs		\$10,000,000	For Alternative 3
Ratio of Repair Area to Damaged Area		2.25	Repair Area = Damaged Area × 2.25
Repair Cost (Direct Cost)	Fondu Fyre	\$300/sq. ft.	Average of \$200/sq. ft. (without welding) and \$400/sq. ft. (with welding)
	Steel Structure	\$168,000/Shuttle	Refer to the estimation in Table 4
Contractor Markup Factor		1.25	Estimate from Refractory Technical Interchange[36]
NASA Overhead Factor		1.05	Estimate from Refractory Technical Interchange[37]
Reduction Factor (Reductions in Damage Using New Refractory Ceramics)		75%	For Alternative 3, based on the expectations: 50% reduction in damage and lengthened repair intervals

The reconstruction costs using the Fondu Fyre was estimated based on the exposed surface areas of the deflectors (~\$15,000 /sq. ft.) and the trench (~\$27,000/sq. ft.). The reconstruction cost should be significantly lower than the repair costs and the research team assumed a unit cost of \$150/sq. ft. based upon a prior reconstruction effort in 1995.[38] Multiplying this unit cost by 21,000 sq. ft. results in a cost of \$3.15M per launch pad, for a combined total of \$6.3 M for both complexes. The research team also assumed that \$2.7M would be required to rehabilitate the underlying structural steel. Consequently, the total cost for the reconstruction was estimated to be \$9M. An additional \$1M was assumed to be required for the startup production and implementation of the technologically advanced refractory ceramic. This figure is likely an upper limit estimate.

5.4.5 Major and Minor Repair Cost Models

The two equation models were used to forecast the cumulative refractory damage areas, and was discussed and illustrated in Figure 21 and Figure 22. They are described as follows:

$$Y = 2.607x^2 + 78.539x \text{ (for LC 39A)}$$
$$Y = 106.28x \text{ (for LC 39B)}$$

Y = cumulative sum of damaged areas
x = cumulative number of Shuttle launches

The procedure for performing these forecasts, using these equation models, is described in detail in Section 5.4.6.

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[36] NASA Refractory Concrete Technical Interchange, August 13, 2008.

[37] NASA Refractory Concrete Technical Interchange, August 13, 2008.

[38] Repair of the Flame Deflectors at LC 39A and LC 39B, Contract No. NAS10-12232, July 6, 1995.

5.4.6 Forecasts in Life Cycle Cost Analysis

The current LCC analysis forecasts repair costs for Fondu Fyre (for Alternatives 1 and 2), the new refractory ceramic (for Alternative 3), and the steel base structure. These forecasts are described in detail as follows.

- Fondu Fyre/Refractory Ceramic repair forecasts: The two equation model is used to predict the cumulative Fondu Fyre damage areas as a function of the cumulative number of launches from LC 39A and LC 39B. From these cumulative measures, the model calculates differentials (annual amount of damage) between the cumulative predictions, and applies the 2.25 repair to damaged area ratio to estimate the required area of repair. Direct repair costs are estimated using the unit repair cost per square foot ($300/sq. ft.). The factors for contractors' markup and NASA's overhead are then applied to determine the loaded cost of repair. For Alternative 3 (to forecast the damage to the refractory ceramic), a "reduction factor" is used. The reduction factor is 75%.
- Steel base structure forecast: The annual average cost of the structural steel repairs ($168K from Table 4) is used to predict future costs. Factors for contractors' markup and NASA overhead are applied to obtain a fully loaded cost of repair. For Alternative 3, the "reduction factor" of 75% is used.

The different alternatives were discussed in Section 5.2. For clarity, they are summarized in Table 11.

Table 11. Specific Variables for Different Alternatives

Alternatives	Specific Variables
Alternative 1	- None
Alternative 2	- Entire reconstruction costs with the existing refractory concrete (Fondu Fyre)
Alternative 3	- Entire reconstruction costs with new refractory ceramics - Research development costs - Reduction factor

5.4.7 Forecasts on Existing Practice – Alternative 1

Alternative 1 assumes that Fondu Fyre WA-1G will be used, without the complete replacement of the flame deflector assembly. Figure 24 forecasts cumulative repair expenditures as a function of Shuttle launches for Alternative 1. The trend of increasing damage (and the resultant repairs) as a function of Shuttle launches is evident.

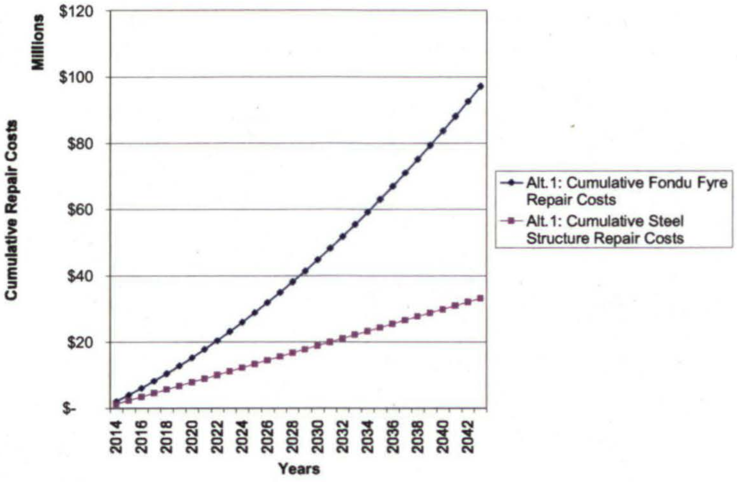

Figure 24. Cumulative Repair Costs – Alternative 1

Figure 25 shows the cumulative net present value (NPV) of total costs. The interest rate discount factor (2.7%) was used to calculate future values throughout the life cycle analysis.

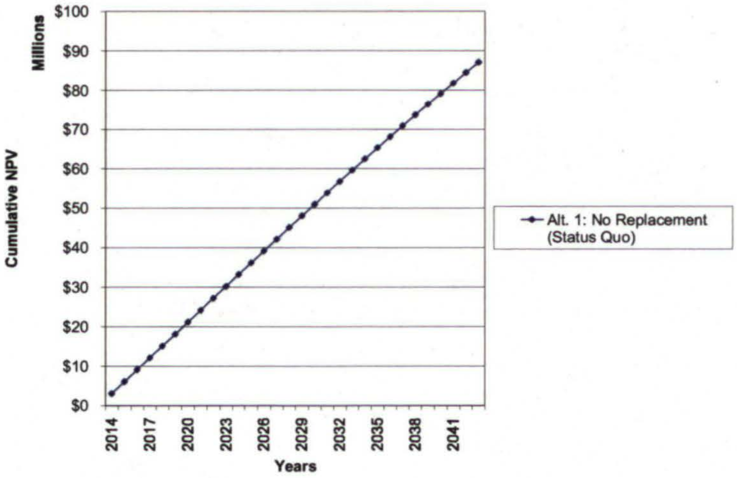

Figure 25. Cumulative NPV of Total Costs – Alternative 1

5.4.8 Forecasts on Reconstruction with Refractory Concrete – Alternative 2

Alternative 2 assumes that the flame deflector system will be completely reconstructed using the current refractory material (i.e., Fondu Fyre WA-1G). As a result of this refurbishment, the flame deflector will exhibit improved resistance to degradation in the early years of the facilities life.

Figure 26 provides a forecast of the cumulative repair costs for Alternative 2. Compared to the forecast for Alternative 1, Alternative 2 shows cumulative repair costs that are lower. An estimate of the cumulative repair costs for Fondu Fyre was made using the same quadratic function as that for Alternative 1, which relies on the cumulative number of launches. Because of the new construction, the launches start from a value of zero, which results in an increased resistance to degradation early in the early years of operation.

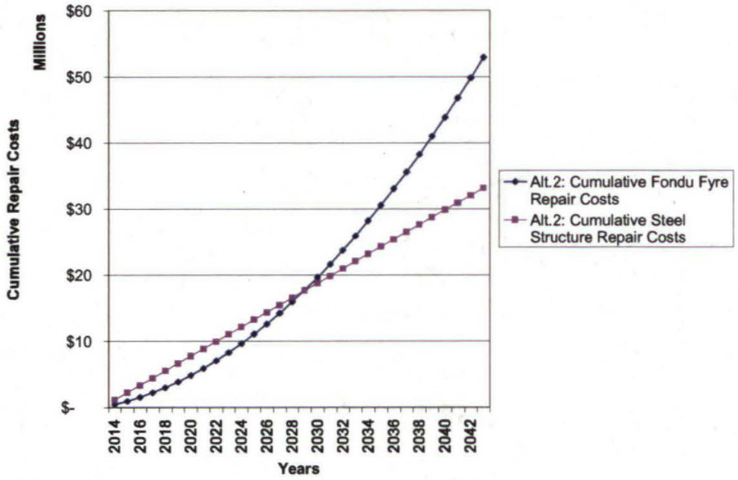

Figure 26. **Cumulative Repair Costs – Alternative 2**

Figure 27 shows the cumulative NPV of total costs including the entire replacement costs. The 2014 construction value is a significant factor in the cost of the facility.

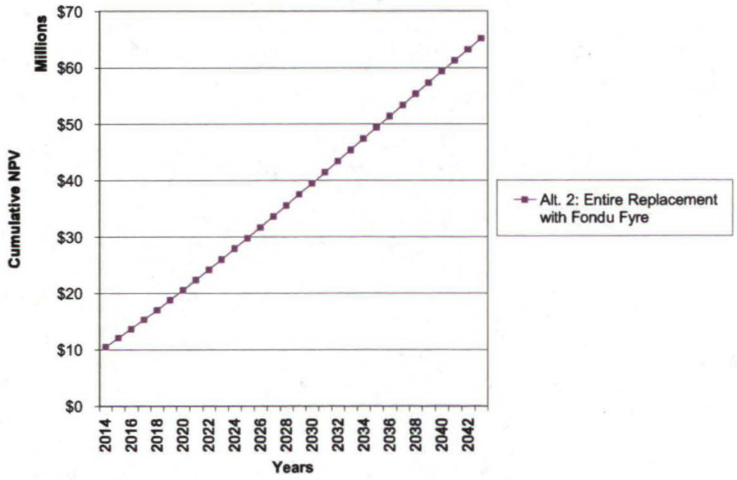

Figure 27. **Cumulative NPV of Total Costs – Alternative 2**

5.4.9 Forecasts on Reconstruction with Technologically Advanced Refractory Materials – Alternative 3

Alternative 3 assumes that LC 39A and LC 39B will be reconstructed using technologically advanced refractory ceramic materials. It is expected that the new protection will result in a system that will remain free from fractures, cracks and spalling; and will exhibit normal wear characteristics with reduced serviceability costs.

Figure 28 shows the forecasted cumulative repair costs for Alternative 3. Compared to the forecasts for the other alternatives, the repair costs for Alternative 3 are significantly lower. This is due to the enhanced protection associated with the new refractory ceramic.

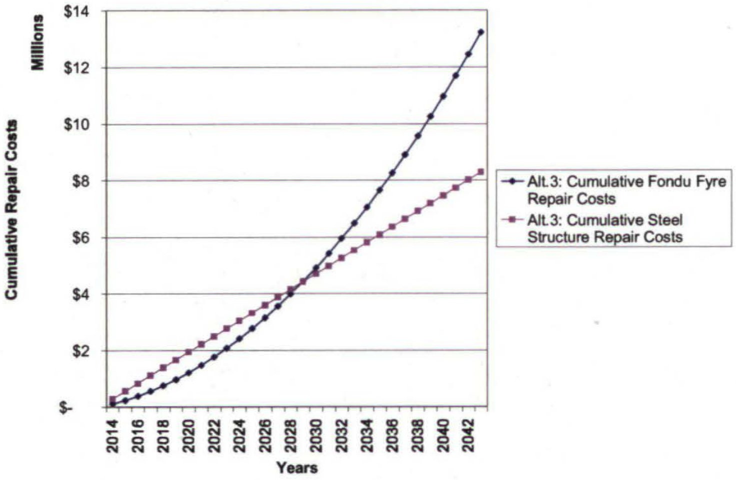

Figure 28. Cumulative Repair Costs – Alternative 3

Figure 29 shows the cumulative NPV costs that are attributable to the replacement of the product, future maintenance, and upfront research costs. Obviously, capital expenditures associated with research and construction efforts are significant.

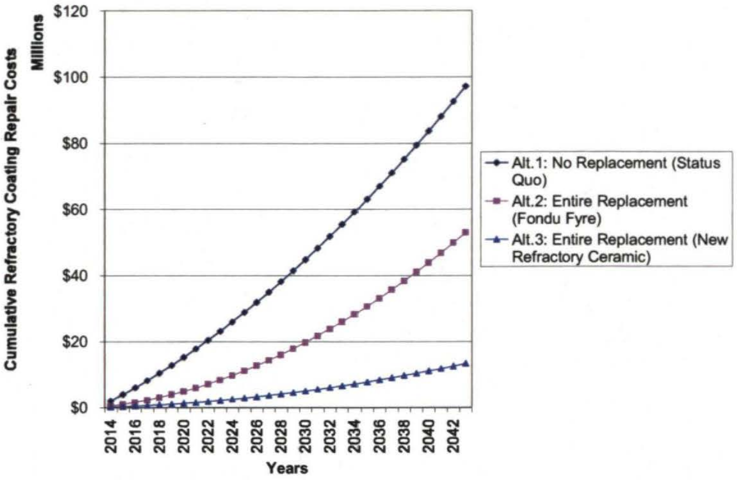

Figure 29. Comparison of Refractory Alternative Repair Costs

5.4.10 Comparison of Alternatives

Figure 30 compares the yearly repair costs for the three alternatives. The comparison clearly shows a significant reduction in repair costs and in improved performance that result from the use of the technologically advanced refractory coating (Alternative 3).

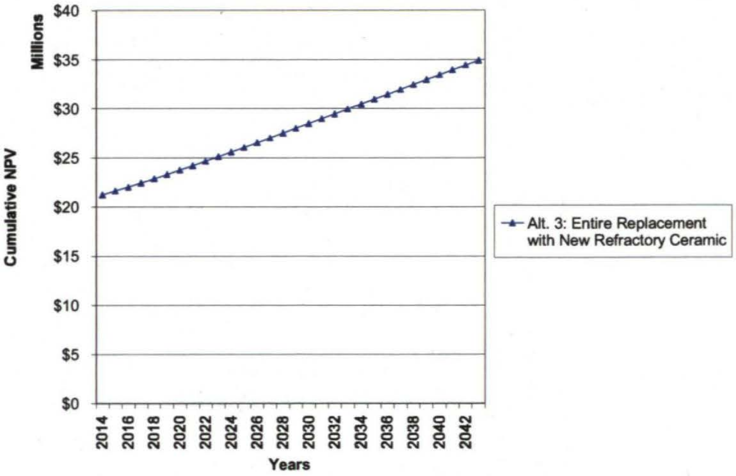

Figure 30. Cumulative NPV of Total Costs – Alternative 3

Figure 31 shows the cumulative NPV costs for the three alternatives. This figure combines all relevant repair costs which include refurbishment costs (Alternatives 2 and 3) and research/development costs (for Alternative 3).

Significant differences in cumulative NPV costs that result from the initial capital requirement are shown in the initial. At the beginning of the life cycle, Alternative 3 had the largest total expenditure in comparison to the other two alternatives. However, due to a reduction in maintenance costs over time, the total cumulative NPV for Alternative 3 becomes significantly lower than those for Alternatives 1 and 2.

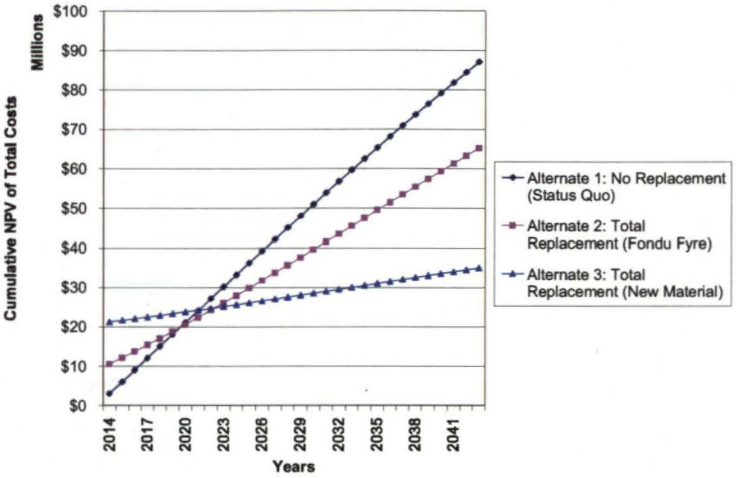

Figure 31. Comparison of Cumulative NPV of Total Costs

Figure 32 provides a comparison of the benefits between the alternatives. Figure 32 shows the cumulative benefit of one alternative over another alternative as determined by taking the difference between their respective cumulative NPV values. As shown in Figure 32, Alternative 2 will produce modest future benefits in comparison to Alternative 3. This is reasonable, since one would expect improved long term performance using a technologically advance refractory material. The benefits associated with using Alternative 2 are lower than Alternative 3, but provide the shortest payback period (approximately 5 years). A comparison of Alternative 3 and Alternative 1 indicates that Alternative 3 exhibits long term benefits that far exceed Alternative 1.

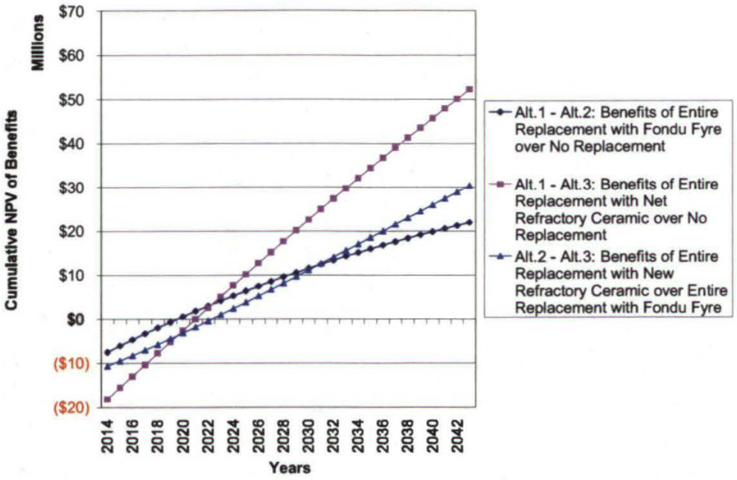

Figure 32. Comparison of Benefits

5.4.11 Determination of Economic Feasibility

Two criteria are commonly used to determine the economic feasibility of one investment decision over another in a LCC analysis. They include the SIR and discounted payback period (DPP).

According to the KSC Cost Engineering Desk Reference,[39] the SIR for an alternative system should be at least 1.5, and the DPP should be in the single digits. The appropriate calculations are as follows:

$$\text{SIR} = \frac{\text{20 years Savings with New System}}{\text{Material Development Costs}} > 1.5 \text{ (the minimum value)}$$

$$\text{DPP} = \text{Years required to recuperate development costs} < 10 \text{ years}$$

Based on the result from the economic model, the following values are obtained.

- For Alternative 3 over Alternative 1
    - Savings to Investment Ratio: $\text{SIR} = \frac{\$32\text{M}}{\$10\text{M}} = 3.2 > 1.5$
    - Discounted Payback Period = 2021 – 2014 = 7 years < 10 years

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[39] Butts, G., "Cost Engineering Desk Reference (Draft)," 2006, p. 246, http://www.ksc.nasa.gov/nasa-only/finance/Cost_EST/index_files/Data/Estimating%20Desk%20Reference_109.pdf **(Last accessed April 9, 2008).**

- For Alternative 3 over Alternative 2
    - Savings to Investment Ratio: $\text{SIR} = \dfrac{\$17\text{M}}{\$10\text{M}} = 1.7 > 1.5$
    - Discounted Payback Period = 2022 – 2014 = 8 years < 10 years

Therefore, the replacement of the launch pads with the advanced refractory material is cost efficient, even though research and development costs are necessary to develop the new product. The benefits result from significant decreases in launch related damage.

Safety benefits associated with the technologically advanced refractory material were not included in this study. By not including these safety benefits, the SIR for Alternative 3 is likely underestimated, and the DPP is likely overestimated.

5.5 Sensitivity Analysis

The economic study determined that Alternative 3 is an economically feasible alternative that can provide significant long term cost benefits to NASA. To assess the sensitivity of the variables used in the analyses and to determine how these impact the cumulative NPV of the benefits from Alternative 3, a sensitivity analysis was performed.

The major variables that were assessed in the sensitivity analysis are listed in Table 12. The sensitivity analysis (completed as part of this study) compares how defined changes in a variable affect the cumulative NPV of benefits when comparing two alternatives. In this case, Alternative 3 over Alternative 2 (which is the competing alternative).

Table 12. Variables for Sensitivity Analysis

Variables	Basis Values	Values to be Tested
Reduction Factor (Reductions in Damage Using New Material)	75% (resultant repair costs will be reduced to a quarter of the current repair costs)	75% to 90%
Direct Repair Cost/sq. ft. (Fondu Fyre)	$300/sq. ft.	$300/sq. ft. to $600/sq. ft.
Number of Shuttle Launches per Year for the Future	5 Shuttles per year	5 to 7 Shuttles per year

5.5.1 Reductions in Damaged Areas

A new refractory ceramic material is expected to remain relatively free from deterioration, and should maintain its initial performance for a longer duration (than Fondu Fyre WA-1G). The assumed reduction factor for the base case was 75% (refer to Table 10). This value is reasonable considering Fondu Fyre was developed in the late 1950s and has experienced minimal improvements.

Advances in materials science and engineering have provided scientists with powerful tools to significantly improve the performance of material systems. Better performance could be expected from the new refractory materials. Thus, three different reduction factors (80%, 85%, and 90%) were assessed, and compared with the 75% reduction base. These are shown in Figure 33.

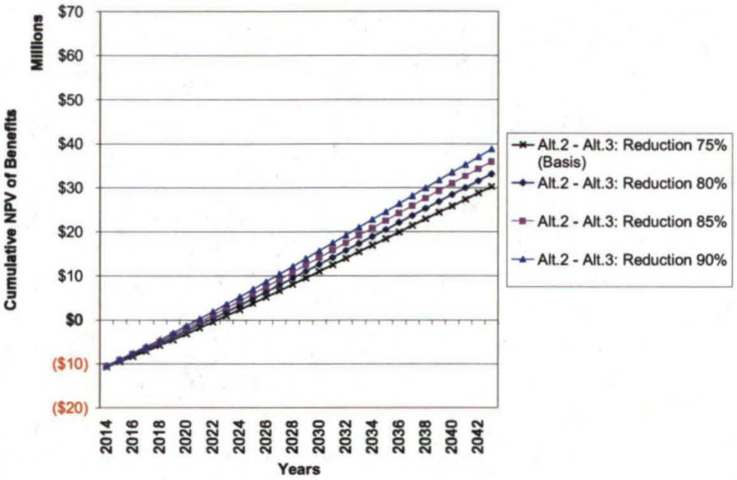

Figure 33. Sensitivity Analysis – Reductions in Damage

The analysis determined that the future benefits will increase with higher reduction factors, although changes in the cumulative net present value of the benefits are not significant.

5.5.2 Direct Unit Repair Cost

Repair costs associated with the existing Fondu Fyre product was determined to be $300/sq. ft. According to a recent article,[40] the significant damage to the flame trench walls during the launch of Discovery (STS-124) resulted in a 4,500 sq. ft. repair. The damaged areas, initially covered by refractory concrete bricks, were repaired using Fondu Fyre. The repair plan was estimated to cost less than $2.7M. The actual repair costs were $2.3M.

A simple calculation indicates that the unit costs are approximately $600/sq. ft. (= $2.7M/ 4,500 sq. ft.) for the initial cost estimation, or $510/sq. ft. (= $2.3M/4,500 sq. ft.) for the actual costs. This indicates that the costs used in this analysis may be low, and as a consequence, the potential influence of unit repair costs of $400, $500, and $600/sq. ft. on cumulative NPV costs was assessed. This sensitivity analysis is shown in Figure 34. Clearly, significant benefits can be realized if larger unit costs are used in the analysis. The model is therefore sensitive to unit costs.

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[40] http://spaceflightnow.com/shuttle/sts124/080626paddamage/

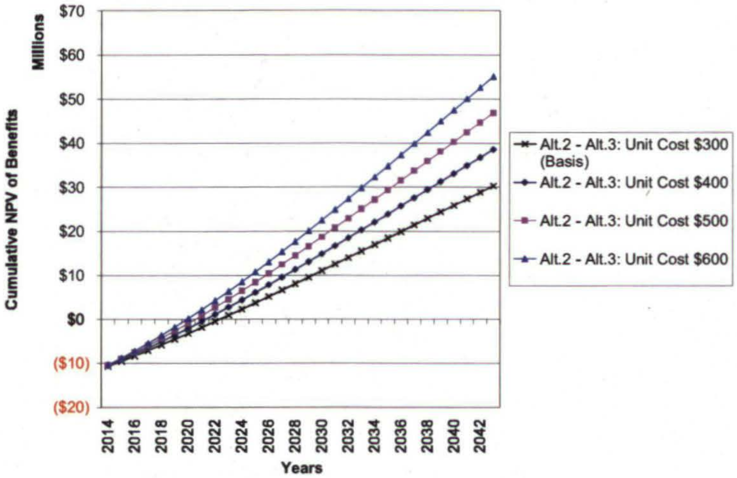

Figure 34. Sensitivity Analysis – Unit Costs

5.5.3 Annual Number of Shuttle Launches for the Future

Since the number of future launches is unknown and since this value can influence the cumulative NPV of the benefits, an assessment was made of the influence of the number of launches on the cumulative NPV of benefits. This assessment is shown in Figure 35. As the figure shows, increasing the number of launches has a significant impact on the cumulative NPV benefits of Alternative 3. Consequently, increases in the number of launches per year will result in enhanced cost benefits (with the technologically advanced refractory material) to NASA's launch program.

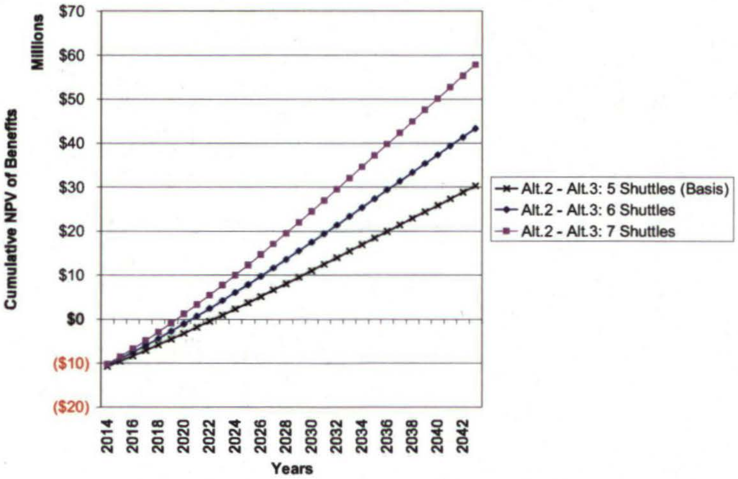

Figure 35. Sensitivity Analysis – Number of Shuttles per Year

5.5.4 Reconstruction Costs in Alternatives 2 and 3

In this LCC analysis, reconstruction costs were assumed to be $9M (Alternative 2 – existing refractory concrete) and $10M (Alternative 3 – new refractory ceramic). In both Alternatives 2 and 3, capital investments associated with reconstruction are significant, so a sensitivity analysis is performed. This procedure will address changes in cumulative benefits associated with alternative reconstruction costs.

Two analyses are performed to address changes in construction costs. The first investigates changes for both Alternative 2 and Alternative 3. Clearly, an economic prediction of future construction costs is not an exact science and can deviate from expected values. The second analysis addresses deviations in construction costs that are related to the implementation of the new material (Alternative 3), such as startup costs associated with the production of the technologically advanced refractory material.

5.5.4.1 Deviation in Construction Costs for Alternative 2 and Alternative 3

The first test assumes a proportional change in reconstruction costs, and compares these changes in benefits with the base case:

- 80% reduction in base costs:
  - Reconstruction costs for Alternative 2: $7.2M (= $9M × 80%)
  - Reconstruction costs for Alternative 3: $8.0M (= $10M × 80%)

- 120% increase in base costs:
  - Reconstruction costs for Alternative 2: $10.8M (= $9M × 120%)
  - Reconstruction costs for Alternative 3: $12.0M (= $10M × 120%)

Figure 36 shows the cumulative NPV of benefits with the assumed reconstruction costs for Alternative 2 and Alternative 3. As shown, the results indicate that both alternatives are not sensitive to a proportional change in reconstruction costs. Since benefits are differences between the cumulative costs for two alternatives, the proportional changes (in Figure 36) do not result in changes to the benefits.

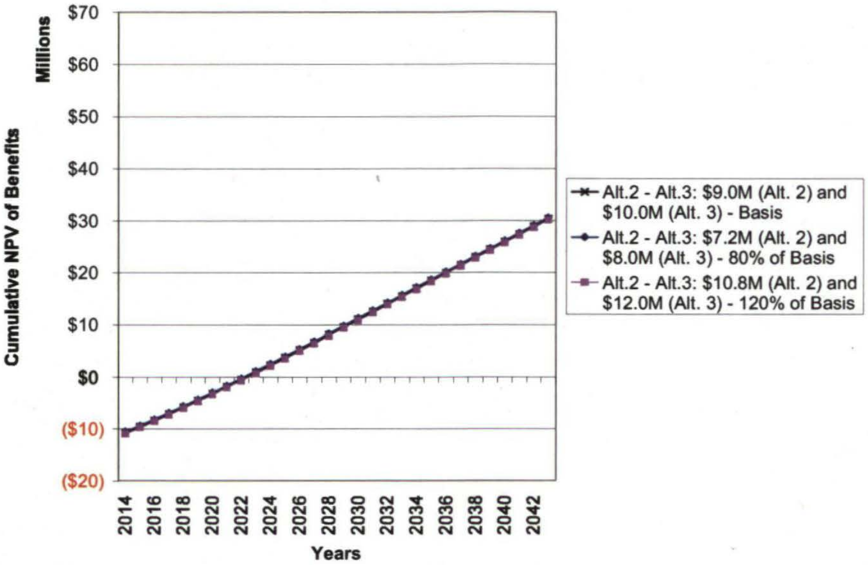

Figure 36. **Sensitivity Analysis – Proportional Changes in Reconstruction Costs**

5.5.4.2 Deviation in Construction Costs for Alternative 3

The second test assumes increases in the reconstruction costs for Alternative 3, while those for Alternative 2 remain at $9M. The test cases assume $11M and $12M reconstruction costs, which represents a $1M and $2M increase over the base value of $10M.

Figure 37 indicates the small changes in the cumulative benefits that result from an increase in reconstruction costs for Alternative 3. The increases in reconstruction costs reduce the amount of the benefits associated with the technologically advanced refractory material and may lead to a longer discount payback period.

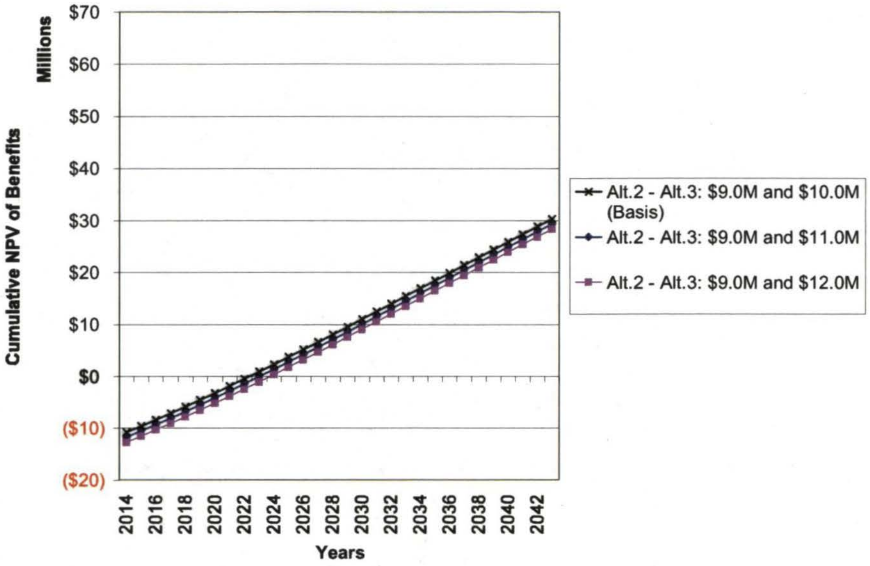

Figure 37. Sensitivity Analysis – Increased Construction Costs for Alternative 3 (Only)

6 CONCLUSIONS

As a result of the constant deterioration from launch heat/blast effects and aggressive environmental exposure, the refractory materials currently used at the launch pad flame deflectors have become very susceptible to failure, resulting in large pieces of refractory materials breaking away from the steel base structure. These pieces are projected at high speed during launch, and jeopardize the launch complex, vehicle, and safety of the crew.

The currently refractory concrete (Fondu Fyre) was developed over 50 years ago and has exhibited unsatisfactory performance. Most refractory materials are designed to perform well when heated at a slow rate and are held at that rate for lengthy periods. The launch complexes at KSC require a material that exhibits superior performance when subjected to extremely high temperatures that increase at a rapid rate. Further requirements include resistance to temperature fluctuations, acoustic loads, ablation, and the corrosive hydrochloric acid in the exhaust of the SRBs during launch. To address these needs, an innovative and technologically advanced refractory material is required to protect the flame deflectors at NASA's launch pads. This report provided the methodology and reasoning to assess the economic feasibility of developing such a material.

This report provides the findings obtained by looking at all the available data on the problems caused by the degradation of the current refractory materials used in the flame deflector and flame trench system. Data related to the cost and frequency of repair for the different subassemblies was collected. These subassemblies included the steel structure of the flame deflector, the refractory concrete that is used to protect it, and the refractory firebrick that is used on the flame trench and walls. The data was analyzed and integrated into a mathematical model that projects future costs as a function of cumulative launches and recurring annualized expenses.

A 20 year life cycle analysis was performed to analyze the economic benefits associated with the development of a technologically advanced refractory system. Using the economic forecasting models that were developed, three alternatives were tested:

- Alternative 1 – No Launch Pad Refurbishment – Repair with Current Fondu Fyre Refractory Material.
- Alternative 2 – Launch Pad Refurbishment – Repair with Current Fondu Fyre Refractory Material.
- Alternative 3 – Launch Pad Refurbishment – Repair with a Technologically Advanced Refractory Material.

The 20 year life cycle analysis showed that Alternative 3 provided a significant reduction in maintenance and repair costs in comparison to the other alternatives. An economic analysis (comparing Alternative 1 to Alternative 3) showed that the capital investment (associated with funding the research to develop the new refractory material) would be recuperated within 7 years. The Savings to Investment Ratio for this investment decision was calculated to be 3.2 at the end of the 20 year life cycle. According to the KSC Cost Engineering Desk Reference, the savings to investment ratio for an alternative system should be at least 1.5, and the discounted payback period should be in the single digits. The choice of Alternative 3 over the other two systems meets these criteria.

A series of sensitivity analyses were performed to address cost assumption concerns associated with:

- Repair cost assumptions
- Number of future launches
- Rehabilitation cost estimates

The sensitivity analyses again showed that the development of a new refractory material (Alternative 3) was preferential to the other alternatives.

This 20 year life cycle analysis shows the benefits associated with the development of a technologically advanced refractory material. This product will provide a significant reduction in maintenance and rehabilitation costs over a 20 year period and will reduce the liberation of FOD during launch. While a cost associated with safety was not addressed in this study, the implications of a catastrophic event resulting from spalled refractory concrete clearly suggest that the development of a new material for NASA's launch complexes is a desirable consideration.

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APPENDIX A. NASA'S SHUTTLE LAUNCH HISTORY

Table A-1. Shuttle Launches at LC 39A

No.	Launch Complex	Launch Date	Mission	Orbiter	No.	Launch Complex	Launch Date	Mission	Orbiter
1	A	4/12/1981	STS-1	Columbia	37	A	2/3/1994	STS-60	Discovery
2	A	11/12/1981	STS-2	Columbia	38	A	4/9/1994	STS-59	Endeavour
3	A	3/22/1982	STS-3	Columbia	39	A	7/8/1994	STS-65	Columbia
4	A	6/27/1982	STS-4	Columbia	40	A	9/30/1994	STS-68	Endeavour
5	A	11/11/1982	STS-5	Columbia	41	A	3/2/1995	STS-67	Endeavour
6	A	4/4/1983	STS-6	Challenger	42	A	6/27/1995	STS-71	Atlantis
7	A	6/18/1983	STS-7	Challenger	43	A	9/7/1995	STS-69	Endeavour
8	A	8/30/1983	STS-8	Challenger	44	A	11/12/1995	STS-74	Atlantis
9	A	11/28/1983	STS-9	Columbia	45	A	9/16/1996	STS-79	Atlantis
10	A	2/3/1984	STS-41-B	Challenger	46	A	2/11/1997	STS-82	Discovery
11	A	4/6/1984	STS-41-C	Challenger	47	A	4/4/1997	STS-83	Columbia
12	A	8/30/1984	STS-41-D	Discovery	48	A	5/15/1997	STS-84	Atlantis
13	A	10/5/1984	STS-41-G	Challenger	49	A	7/1/1997	STS-94	Columbia
14	A	11/8/1984	STS-51-A	Discovery	50	A	8/7/1997	STS-85	Discovery
15	A	1/24/1985	STS-51-C	Discovery	51	A	9/25/1997	STS-86	Atlantis
16	A	4/12/1985	STS-51-D	Discovery	52	A	1/22/1998	STS-89	Endeavour
17	A	4/29/1985	STS-51-B	Challenger	53	A	6/2/1998	STS-91	Discovery
18	A	6/17/1985	STS-51-G	Discovery	54	A	12/4/1998	STS-88	Endeavour
19	A	7/29/1985	STS-51-F	Challenger	55	A	2/11/2000	STS-99	Endeavour
20	A	8/27/1985	STS-51-I	Discovery	56	A	5/19/2000	STS-101	Atlantis
21	A	10/3/1985	STS-51-J	Atlantis	57	A	10/11/2000	STS-92	Discovery
22	A	10/30/1985	STS-61-A	Challenger	58	A	2/7/2001	STS-98	Atlantis
23	A	11/26/1985	STS-61-B	Atlantis	59	A	4/19/2001	STS-100	Endeavour
24	A	1/12/1986	STS-61-C	Columbia	60	A	8/10/2001	STS-105	Discovery
25	A	1/9/1990	STS-32	Columbia	61	A	3/1/2002	STS-109	Columbia
26	A	2/28/1990	STS-36	Atlantis	62	A	6/5/2002	STS-111	Endeavour
27	A	11/15/1990	STS-38	Atlantis	63	A	11/23/2002	STS-113	Endeavour
28	A	4/28/1991	STS-39	Discovery	64	A	1/16/2003	STS-107	Columbia
29	A	8/2/1991	STS-43	Atlantis	65	A	6/8/2007	STS-117	Atlantis
30	A	9/12/1991	STS-48	Discovery	66	A	8/8/2007	STS-118	Endeavour
31	A	11/24/1991	STS-44	Atlantis	67	A	10/23/2007	STS-120	Discovery
32	A	1/22/1992	STS-42	Discovery	68	A	2/7/2008	STS-122	Atlantis
33	A	3/24/1992	STS-45	Atlantis	69	A	3/11/2008	STS-123	Endeavour
34	A	6/25/1992	STS-50	Columbia	70	A	5/31/2008	STS-124	Discovery
35	A	12/2/1992	STS-53	Discovery	71	A	11/14/2008	STS-126	Endeavour
36	A	4/26/1993	STS-55	Columbia					

Table A-2. Shuttle Launches at LC 39B

No.	Launch Complex	Launch Date	Mission	Orbiter	No.	Launch Complex	Launch Date	Mission	Orbiter
1	B	1/28/1986	STS-51-L	Challenger	28	B	7/13/1995	STS-70	Discovery
2	B	9/29/1988	STS-26	Discovery	29	B	10/20/1995	STS-73	Columbia
3	B	12/2/1988	STS-27	Atlantis	30	B	1/11/1996	STS-72	Endeavour
4	B	3/13/1989	STS-29	Discovery	31	B	2/22/1996	STS-75	Columbia
5	B	5/4/1989	STS-30	Atlantis	32	B	3/22/1996	STS-76	Atlantis
6	B	8/8/1989	STS-28	Columbia	33	B	5/19/1996	STS-77	Endeavour
7	B	10/18/1989	STS-34	Atlantis	34	B	6/20/1996	STS-78	Columbia
8	B	11/22/1989	STS-33	Discovery	35	B	11/19/1996	STS-80	Columbia
9	B	4/24/1990	STS-31	Discovery	36	B	1/12/1997	STS-81	Atlantis
10	B	10/6/1990	STS-41	Discovery	37	B	11/19/1997	STS-87	Columbia
11	B	12/2/1990	STS-35	Columbia	38	B	4/17/1998	STS-90	Columbia
12	B	4/5/1991	STS-37	Atlantis	39	B	10/29/1998	STS-95	Discovery
13	B	6/5/1991	STS-40	Columbia	40	B	5/27/1999	STS-96	Discovery
14	B	5/7/1992	STS-49	Endeavour	41	B	7/23/1999	STS-93	Columbia
15	B	7/31/1992	STS-46	Atlantis	42	B	12/19/1999	STS-103	Discovery
16	B	9/12/1992	STS-47	Endeavour	43	B	9/8/2000	STS-106	Atlantis
17	B	10/22/1992	STS-52	Columbia	44	B	11/30/2000	STS-97	Endeavour
18	B	1/13/1993	STS-54	Endeavour	45	B	3/8/2001	STS-102	Discovery
19	B	4/8/1993	STS-56	Discovery	46	B	7/12/2001	STS-104	Atlantis
20	B	6/21/1993	STS-57	Endeavour	47	B	12/5/2001	STS-108	Endeavour
21	B	9/12/1993	STS-51	Discovery	48	B	4/8/2002	STS-110	Atlantis
22	B	10/18/1993	STS-58	Columbia	49	B	10/7/2002	STS-112	Atlantis
23	B	12/2/1993	STS-61	Endeavour	50	B	7/26/2005	STS-114	Discovery
24	B	3/4/1994	STS-62	Columbia	51	B	7/4/2006	STS-121	Discovery
25	B	9/9/1994	STS-64	Discovery	52	B	9/9/2006	STS-115	Atlantis
26	B	11/3/1994	STS-66	Atlantis	53	B	12/9/2006	STS-116	Discovery
27	B	2/3/1995	STS-63	Discovery					

APPENDIX B. NASA'S FONDU FYRE HISTORICAL LIBERATION

Table B-1. Fondu Fyre Historical Liberation – LC 39A

Mission	Damage History				SQ FT Repair Area								Comments
	Date of Damage Record	Extent of Damage	STS	PAD	STS	PAD	SRB MFD	SSME MFD	West SFD	East SFD	Trench Wall	Trench Floor	
STS-1	4/21/1981	Lost Bricks from Flame Trench Floor Near SRB MFD. Size of areas where bricks lost approx. 10' x 3', 5' x 6 ", 3' x 6" and 3' x 6"	1	A						41		N	
	4/21/1981	Wall cap damage									x		
STS-2	1/12/1982	Lost Bricks from Flame Trench Floor.	2	A						x			
STS-8	9/7/1983	Replace portion of refractory concrete of SRB/SSME MFD during STS-10 downtime	8	A	x	x							
STS-61-C	9/1/1989	Cracks in MFD. Cracks in SFD	61C	A	?	?	?	?					
STS-36	2/28/1990	SRB MFD lower west lip	36	A	x								
STS-39	4/28/1991	SRB MFD 12 sq. ft. on east lip and 25 sq. ft. on west lip of Fondu Fyre missing, SRB MFD and Trench Wall damaged grid steel and refractory.	39	A	x								
	4/30/1991		39		x				x				
STS-43	8/2/1991	Approx. 20% Fondu Fyre missing, SRB MFD lower lip East and West side, upper east lip, SRB MFD and Trench Wall damaged grid steel and refractory. Grid steel and refractory missing	43	A	970							Y	0.2*4852 sq ft
	8/5/1991		43		675							N	
STS-48	9/17/1991	SRB MFD and Trench Wall damaged grid steel and refractory. Grid steel and refractory missing Concrete and Grid steel missing/damaged; 4' x 8' lower east on MFD, 2' x 4' 2 places on lower west side MFD, 1' x 2' upper west side MFD, lower lip on both side flame deflectors.	48	A	120				x			Y	
STS-44	11/25/1991	SRB MFD and Trench Wall damaged grid steel and refractory. Grid steel and refractory missing	44	A	?	?	x	x					
	11/25/1991		44			330		32				Y	
STS-42	1/22/1992	SRB MFD west side 6' x 10' missing at lip. SRB MFD east side 8' x 10' missing at lip. SRB MFD refractory and grid steel damaged/missing in various places SRB MFD and Trench Wall damaged grid steel and refractory. Grid steel and refractory missing	42	A	x								
	1/23/1992		42		450							Y	
	1/23/1992		42		50				30			N	

Mission	Damage History				SQ FT Repair Area								Comments
	Date of Damage Record	Extent of Damage	STS	PAD	STS	PAD	SRB MFD	SSME MFD	West SFD	East SFD	Trench Wall	Trench Floor	
STS-45	4/10/1992	SSME and SRB MFD and Trench Wall damaged. Refractory damaged/eroded exposing grid steel.	45	A	330								
STS-50	6/26/1992	SRB MFD and Trench Wall damaged grid steel and refractory. Grid steel and refractory missing Large sections of ablative missing beneath both east and west side SRB exhaust holes. Ablative material at bottom of SRB flame deflector damaged more than usual. Many pieces blown to the north. 8' x 12' missing ablative beneath west SRB hole. 10' x 15' missing ablative beneath east SRB hole. Cracks along lower lip of east SFD.	50	A	x				x				
STS-53	12/2/1992	MFD Fondu Fyre missing in various places on both SSME and SRB sides.	53	A	x	x							
	12/3/1992		53		x	x						Y	no sq ft data
STS-55	4/26/1993	East SFD pieces missing at lower lip, SRB MFD Fondu Fyre and grid steel torn away at east side bottom lip 10' x 20', SSME MFD (qty. 3) 1' x 3' pieces missing minor cracking/missing concrete on Side Flame Deflector	55	A	200	9		x					
STS-60	2/3/1994	East SFD Fondu Fyre missing in various locations	60	A			?	?					
	2/7/1994		60					40				Y	
STS-65	7/8/1994	4 bricks missing from north end of flame trench SSME MFD 4' x 4' eroded grid steel and 4 cracks 4' long x 2 " wide, East Side Flame Deflector chips 4" x 4" in 2 places West SFD SRB side damaged or missing Fondu Fyre along lower lip. SSME MFD damaged or missing Fondu Fyre at center. East side wall cap damage. Damaged Fondu Fyre along Flame Trench Floor and west Side Flame Trench Wall	65	A		x		x	?	?			
	7/13/1994		65			300	20		50	100	100	Y	
STS-68	9/30/1994	SSME Flame Trench Wall Cap Damaged	68	A		x							
STS-67													
STS-50	6/25/1995	SRB MFD grooves and depressions on lower east end	50		246			x					
STS-71	6/27/1995		71	A	x								
STS-69	9/7/1995	North Flame Trench Floor buckled, SRB MFD minor cracking along east lip	69	A	x					x			

Mission	Damage History				SQ FT Repair Area								Comments
	Date of Damage Record	Extent of Damage	STS	PAD	STS	PAD	SRB MFD	SSME MFD	West SFD	East SFD	Trench Wall	Trench Floor	
STS-82	2/14/1997	MFD damage 2 sq. ft. east side lower lip, 1 sq. ft. west side lower lip, 2 sq. ft. east side approx. 8' below top	82	A	5							Y	
STS-83	4/5/1997	Pad safety reported material loss and damage to the firewall in the south flame trench. Debris team inspection of the north flame trench showed a 2-foot by 8-inch area of missing firewall material from the flame deflector. Pieces of material were found.	83	A									
STS-84	5/16/1997	SRB MFD chip missing 10' from bottom and 15' from west side and crack 3' from bottom 5' from west side	84	A	x							N	no sq ft data
STS-94	7/25/1997	SRB MFD damage along west side lower lip. SSME MFD 1.5' x 3' and 1.5' x 2' damage just east of centerline	94	A	x	10							no sq ft data
STS-85	8/12/1997	Loose and cracked Fondu Fyre SRB MFD and SSME MFD. SSME south slope crack 5' x 3' located 7' down from top edge and 8' from east side West SFD missing 8" x 6' along bottom starting at center and running south	85	A	x	x							no sq ft data
	9/2/1997		85			15						N	
	9/2/1997		85				6					N	
STS-86	12/8/1997	SRB MFD approx. 25 sq. ft. of Fondu Fyre needs repaired. Loose bricks on 2nd seam south of SSME MFD lip 25' above floor of trench	86	A	125							N	
STS-89	2/13/1998	MFD damage north and south West SFD missing 8" x 6' starting at center and running south and 8" x 2' starting 1' from north end and running south	89	A	2	2						N	repair 48hrs
	2/19/1998		89				8					N	
STS-99	2/11/2000	Loose refractories in Flame Trench	99	A					?	?			
STS-98	2/8/2001	SSME MFD some loss of refractory. SRB MFD some loss of refractory. Flame trench minimal loss of refractory and exposed grid steel	98	A	x	x							
STS-100	4/19/2001	SRB MFD some loss of refractory. SRB Flame Trench growing amount of exposed grid steel.	100	A	x								
STS-111	6/5/2002	Fondu Fyre 6"x73/4 x4" think, and numerous smaller chunks	111	A									

Mission	Damage History				SQ FT Repair Area								Comments
	Date of Damage Record	Extent of Damage	STS	PAD	STS	PAD	SRB MFD	SSME MFD	West SFD	East SFD	Trench Wall	Trench Floor	
STS-117	6/12/2007	Minor damage to MFD Large thin pieces scattered within 100' of North throat of Flame Trench. Found on South pad surface almost to slope Several pieces. Found on East Pad Surface. Found South East pad surface Several pieces	117	A	?	?							
STS-118	8/14/2007	East Side North Trench Wall Cap lost some Fondu Fyre. No major damage/anomalies. Some loose refractory was removed. SSME flame trench wall loose & missing bricks.	118	A							x		
	8/14/2007		118		?	?							
	8/17/2007		118						x				repair 68.5 hrs
STS-120	10/23/2007	SRB MFD Fondu Fyre lost in several locations. SRB MFD missing Fondu Fyre	120	A	x								
	10/24/2007		120		x								
STS-122	2/13/2008	SRB MFD very minor damage. A 12" x 12" area in the upper east section may have delaminated. A smaller area 6" x 4" liberated.	122	A	x								
STS-123	3/13/2008	East Side Wall Fillet above MFD Flame Fence refractories liberated approx. 3' x 12'. West Side Wall Fillet 3' x 3'	123	A					x				
STS-124	6/4/2008	West SFD lost 6" x 6" x 12" piece of Fondu Fyre, East Flame Trench Wall approx. 2,000 sq. ft. of brick liberated	124	A			x						
	6/4/2008		124						2000				
STS-126			126	A									

Table B-2. Fondu Fyre Historical Liberation – LC 39B

Mission	Damage History				SQ FT Repair Area								Comments
	Date of Damage Record	Extent of Damage	STS	PAD									
STS-51-L	5/13/1986	Approx. 34' x 7' area of bricks lost 120' North of the MFD.	51L	B						238			
STS-26	8/5/1985	SRB MFD some erosion and small chip in upper west portion increased in size	26	B	x								
STS-27	12/12/1988	SRB MFD missing section of Fondu Fyre 8' from trench wall	27	B	x							N	no sq ft data
STS-41	10/17/1990	SRB MFD and Trench wall damaged during launch. Refractory and grid steel is damaged in various places. Surface appears heavily eroded on approx. 20 percent and is cracked or raised in various places. Particle rising vertically out of exhaust hole as vehicle clears frame does not contact vehicle.	41	B	275				100			N	
STS-35	12/7/1990	SRB MFD and Trench Wall are damaged/missing in various places	35	B	120				600			Y	
STS-37	4/15/1991	SRB MFD and Trench Wall damaged grid steel and refractory. Comments: A dark particle appeared in the flame trench north of the MLP (film review). Three particles were ejected out of the north flame trench.	37	B	200				25			N	
STS-40	6/7/1991	SRB MFD and Trench Wall damaged grid steel and refractory. Grid steel and refractory missing. Combined comments: A minimum of 4 dark/long particles appeared against the horizon after being ejected out of the SRB flame trench.	40	B	x				x				outside contract
STS-49													
STS-46	8/3/1992	SRB MFD Damage. 2 small chunks of Fondu Fyre were blasted off.	46	B	30							N	
STS-47	9/14/1992	SRB MFD Fondu Fyre missing along lip under the east SRB Exhaust Hole Fondu Fyre missing along east blast hole impingement area (~4' x 6')	47	B	x								
STS-52	10/26/1992	Wall Cap Along the North end of Flame Trench is crumbling in Various Places.	52	B							x	N	no sq ft data
STS-56	4/15/1993	SRB MFD refractory concrete damaged.	56	B	55							N	
STS-57	6/22/1993	SRB MFD refractory concrete missing along lip. 4' x 6' section of Fondu Fyre refractory concrete is missing	57	B	50							Y	

Mission	Damage History				SQ FT Repair Area								Comments
	Date of Damage Record	Extent of Damage	STS	PAD									
STS-51	9/14/1993	Section of the lower steel lip of the East SFD was blown off during launch SRB MFD refractory concrete missing along flame fence at the lower west corner	51	B				30				Y	
	9/14/1993		51		40							N	
STS-58	10/19/1993	SRB MFD refractory concrete and grid steel missing along the lower east lip and the east flame fence.	58	B	100							Y	
STS-61	12/2/1993	Minor damage along lower east lip of MFD, missing 3' x 3' and 1' x 2' sections of concrete SRB MFD Fondu Fyre damaged during launch along lower east lip. East side flame trench wall cap damaged. Minor damage along the lower east lip of main flame deflector. Refractory concrete missing in 2 places (~3' x 3', 1' x 2'). Ablative missing along flame trench wall cap, east side 2 places. East work platform grating damaged from fondue hitting underside	61	B	x								
STS-62	2/7/1994	Lower east SRB deflector Fondu Fyre broken loose several places	62	B	55						300	Y	
STS-64	9/12/1994	SRB MFD damaged/missing Fondu Fyre along east side lower lip. East side wall cap damaged	64	B	120						125	N	
STS-66	11/3/1994	SRB MFD missing area midway up west side and along the lower east side SRB MFD damage midway up west side and along east side lip	66	B	x								
	11/8/1994		66		x								no sq ft data
STS-70	7/13/1995	SRB MFD missing 3' x 3' area along lower east lip and cracked midway up on the west side	70	B	x								
STS-75	2/24/1996	SRB MFD 2' x 3' chip, North Flame Trench Floor 1' x 2' piece missing	75	B	x					x			
STS-78	6/27/1996	SFD Damage	78	B			45	45				Y	
STS-87	2/13/1998	SRB MFD 1 sq. ft. chip on lip 6 ft. from east edge and 2' x 4' chip 8' from the west and 12' above the lip	87	B	9							N	
STS-95	12/3/1998	SRB MFD crack on seam approx. 30' long. SSME MFD 4.5' x 3' damage at bottom of slope	95	B	60	15						Y	

Mission	Damage History				SQ FT Repair Area								Comments
	Date of Damage Record	Extent of Damage	STS	PAD									
STS-93	7/25/1999	SRB MFD west side 2' x 3' missing at lip. SRB MFD east side 3' x 5' missing at lip. MFD damage on/near lower lip at 3 places, corner chip on east wall above the lip, and area of recent repair on the west wall.	93	B	x								
	8/24/1999		93		?	?			x				repair 22 hrs
STS-102	3/8/2001	SRB MFD general erosion; 60" x 2" repair and 8' x 3' repair in NE corner	102	B	x								
STS-104	7/12/2001	SRB MFD approx. 40 sq. ft. of repairs needed in 11 different areas. Approx. 34" x 51" of refractory lost and grid steel eroded.	104	B	x								
STS-112	10/8/2002	SRB MFD right side: 4' x 6' chip at lip and 4' x 4' approx. 15 ft up slope. SRB MFD left side: 3' x 4' at lip and 3' x 10' with missing Grid steel and studs approx. 6' up slope. Flame Trench floor has exposed grid steel 3' x 4' in several places. North Flame trench Deflector, Significant erosion from left and right boosters; fence is damaged with debris at base.	112	B	x					x			
STS-114	8/4/2005	MFD lost some Fondu Fyre	114	B	?	?							repair 3,099.5 hrs
STS-121	7/5/2006	Loose bricks on east flame trench wall SRB MFD missing upper S.W. corner	121	B					x				
	7/6/2006		121		x								
STS-115	5/23/2006	SRB MFD very minor damage. Loose fist sized piece of refractory on west fence.	115	B	x								
	9/13/2006	East Flame Trench Wall minor spalling of Refractory adjacent to MFD	115							x			
STS-116	11/11/2006	SSME MFD some existing exposed grid steel Fondu Fyre found on pad surface under East side flame deflector shield.	116	B		x							

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APPENDIX C. ANALYSIS ON DAMAGE OCCURRENCE

The NASA's Fondu Fyre damage history provides a qualitative description of damages identified after Shuttle launches. A close look at the data finds that some Shuttle launches resulted in damages, while others did not. The various damages in the NASA's Fondu Fyre damage history can be classified by the location of damage as follows:

- Flame trench walls and cap
  - Trench walls
  - Wall cap
- Flame trench floors
- MFD (Main Flamed Deflector)
  - SRB MFD (Solid Rocket Booster Main Flame Deflector)
  - SSME MFD (Space Shuttle Main Engine Main Flame Deflector)
- SFD (Side Flame Deflector)

Using the Fondu Fyre damage data, the numbers of Shuttles with and without post launch repair were estimated. By counting the number of repairs for each component, the probability of damage can be measured for each component using the following equation:

$$\text{Probability of Damage Occurrence} = \frac{\text{Number of Damage Occurrences to A Component}}{\text{Number of Shuttle Launches}}$$

Table 3-1 provides the estimated probabilities of damage for each component over the last 28 years (1981~2008). As shown, LC 39A and LC 39B have somewhat different damage probabilities for the classified components. Generally speaking though, the SRB MFD had a higher probability of damage than the SSME MFD.

Table C-1. Probabilities of Damage Occurrences for Each Component

Launch Complex	Total Number of Shuttle Launches	Estimates	Trench Wall		Trench Floor	MFD		SFD
			Refractory Concrete	Cap	Refractory Concrete	SRB	SSME	Fondu Fyre
39A	71	Frequency	9	3	5	27	13	13
		Probability	12.7%	4.2%	7.0%	38.0%	18.3%	18.3%
39B	53	Frequency	6	3	4	27	4	3
		Probability	11.3%	5.7%	7.5%	50.9%	7.5%	5.7%

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