COVER PAGE

Title of Design: Twice Repurposed Crumb Rubber as a Jet Fuel Solidifier
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Twice Repurposed Crumb Rubber as a Jet Fuel Solidifier

Boulder Environmental Solutions Team

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Executive Summary

In this report, the Boulder Environmental Solutions Team (BEST), a design team comprised of four environmental engineering undergraduates from the University of Colorado Boulder, presents an innovative method for the cleanup and containment of jet fuel spills at Denver International Airport (DIA) to the Federal Aviation Administration (FAA) Design Competition for Universities: *Twice Repurposed Crumb Rubber as a Jet Fuel Solidifier*. This design offers DIA and other airports a unique opportunity to divert a waste stream from the automotive industry to satisfy the needs of daily airport operations, and then to utilize the resultant waste stream in asphalt production processes.

In order to produce a feasible and practical method of containment and cleanup of spills, the BEST worked closely with the Director of Environmental Programs, Scott Morrissey, to tailor this design to meet the needs of the spill response team at DIA. According to Mr. Morrissey, jet fuel spills under 25 gallons (JFS-U25) in and around paved fueling areas are the most common and problematic spills at DIA, with the median spill size being around 3 gallons. Currently, these spills are cleaned up using generic oil absorbents and shipped off-site to either a hazardous waste disposal facility or a landfill. Mr. Morrissey expressed interest in implementing a more sustainable process while maintaining the speed and effectiveness of the current practice. Focusing on efficient cleanup and remediation of JFS-U25, the BEST investigated and screened three alternative designs: microbial degradation of hydrocarbons, increased fuel evaporation via infrared light, and oil solidifier technology. The BEST determined that oil solidifier absorbents exhibit the greatest potential for an improved design.

This design encompasses the supply, use, and fate of crumb rubber hydrocarbon solidifiers pertaining to DIA and other airport facilities. Powdered crumb rubber, a product made from used automobile tires, is often used in asphalt production processes. It can also be used as a hydrocarbon solidifier. This design suggests utilizing the existing spill response infrastructure at DIA and replacing the current absorbents with powdered crumb rubber from a tire recycling facility. After use at DIA, the spent crumb rubber is to be transported to a local asphalt production plant, where it can be regenerated and incorporated into the production process. The capital cost of this design is estimated at $9,500, a sum that is very competitive to current cleanup costs. The BEST is pleased to deliver this practical and innovative design to the FAA and DIA.

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List of Acronyms

BEST	Boulder Environmental Solution Team
BTEX	Benzene, Toluene, Ethyl benzene, and Xylene
CRM	Crumb Rubber Modifier
DIA	Denver International Airport
DNA	Deoxyribonucleic Acid
EMS	Environmental Management System
EPA	Environmental Protection Agency
EVEN	Environmental Engineering
FAA	Federal Aviation Administration
IR	Infrared
JFS-U3	Jet Fuel Spill Under 3 gallons
JFS-U25	Jet Fuel Spill Under 2 gallons
MSDS	Material Safety Data Sheet
NEPA	National Environmental Policy Act
RCRA	Resource Conservation and Recovery Act
SBR	Styrene-Butadiene Rubber
S-SBR	Solution of Styrene-Butadiene Rubber
UCB	University of Colorado Boulder
UST	Underground Storage Tank

1.0 Problem Statement and Background

With over 87,000 flights per day in the United States (RightThisMinute, 2012) cutting across over 19,700 airports (AirlinesforAmerica, 2014), environmental stewardship must be at the forefront of airport operations. Hazardous substances are used for many airport procedures and present a constant threat not only to immediate airport processes, but to the surrounding ecology and water systems. While most airports have strict protocols to combat these risks, improvements can always be made to lessen the impacts on the environment.

Opening in February of 1995, Denver International Airport (DIA) became the country's largest airport at 53 square miles and provided an instantaneous and much needed boost to the Colorado economy (Denver International Airport, 2014). Because of the enormous acreage and nonstop traffic occurring every single day, the risks of environmental contamination from fuel spills are far greater than at most facilities. To combat these risks, guidelines have been created in their Environmental Management System (EMS), which "outlines a series of guidelines, policies, procedures and processes that address environmental impacts in day-to-day business activities" (DIA Business Center, 2014). With 28 miles of fueling pipes that accommodate 1,000 gallons per minute of jet fuel, the threat of a catastrophic spill seems imminent and demonstrates the necessity of these strict environmental regulations (Denver International Airport, 2014). However according to an interview with DIA's Director of Environmental Programs, Scott Morrissey, despite this alarming danger that carries extreme consequences, the most probable threat to their efforts involves jet fuel spills under 25 gallons (JFS-U25).

Figure 1 DIA's Jeppesen Terminal (UKIP Media)

At DIA, the number of reported hazardous spills has increased from 201 spills in 2010 to 291 spills in 2012 (Morrissey, 2014). These spills can occur through a variety of processes such as refueling using the hydrant fueling system, fueling trucks, portable fuel cans, or through the leakage from above ground storage tanks or underground storage tanks (USTs) (Environmental Guidelines, 2012). An aerial map of DIA can be seen in Figure 1 and 2. Upon examination of a report documenting 20 previous JFS-U25 spills at DIA, it was discovered that Jet A spills do occur from many of the sources listed above and are often less than three gallons (JFS-U3).

Although not required to report JFS-U25 spills to regulatory agencies, the staff at DIA meticulously tracks every spill as part of their environmental due diligence and in order to make note of any possible contamination for future on-site procedures. While not all JFS-U25 spills are jet fuel—some may be gasoline or deicing fluid from other airport processes—Mr. Morrissey and his crew are interested in finding a fresh approach to neutralizing JFS-U25, and more applicably, JFS-U3. Current operating procedures use inexpensive absorbent materials such as sawdust or cat litter and throw the used materials into a hazardous waste landfill.

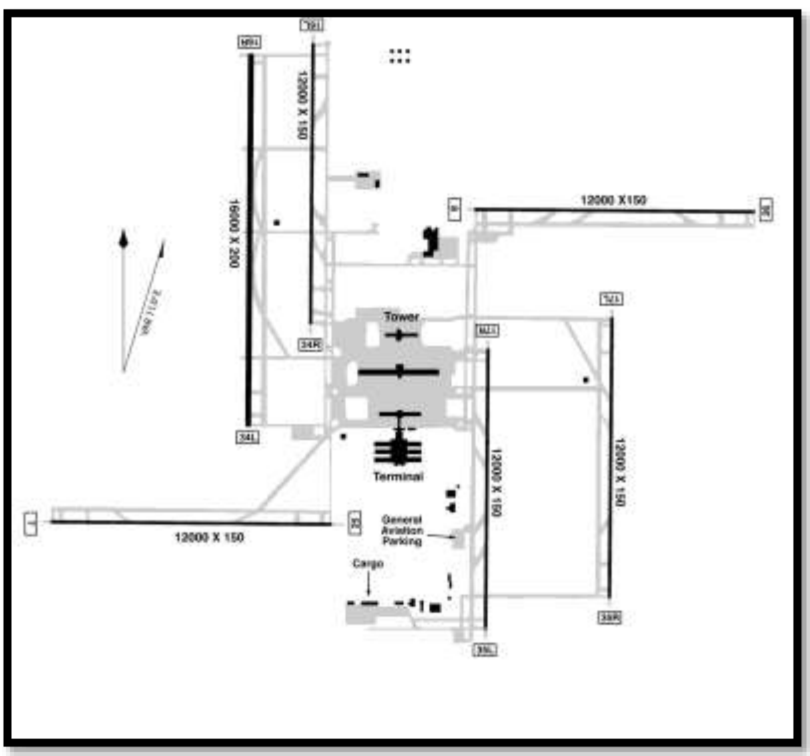

Figure 2: Aerial map of DIA, highlighting the size of the runways and possible areas of contamination (FAA)

Although the cleanup of JFS-U25 appears to be relatively effective and reasonably priced, the BEST will explore possible improved remediation options to be implemented at DIA. Primary goals for our design include:

- Minimizing safety risks
- Low-cost materials
- Feasibility
- Innovation
- Minimal environmental impacts

The BEST will strive to achieve these goals and fulfill the needs of Mr. Morrissey and the Environmental Programs team at DIA by creating an original and sustainable design.

2.0 Regulations, Constraints, and Criteria

Environmental regulations pertinent to airport operations include: the National Environmental Policy Act (NEPA), Resource Conservation and Recovery Act (RCRA), and various FAA policies and procedures. At present, the release and fate of JFS-U25 are not subject to any regulatory constraints and are treated as non-reportable quantities at DIA (Morrissey, 2014). It follows that any proposed alternative method of cleanup and remediation also falls below national and state regulatory guidelines. Even so, as part of due diligence in practice, the EMS requires that employees report and record all spills, regardless of size (Morrissey, 2014). Review of these records indicates that nearly all spills are removed through some sort of absorbent application and rarely reach an entrance to the drainage system. These spills and their containing absorbent are removed off-site to either a landfill or a hazardous waste disposal facility (Morrissey, 2014). To prevent contamination of underlying soil and water systems, DIA operates a fully-contained drainage system which captures and isolates any fugitive spills that would otherwise enter the public drainage network. DIA's drainage system directs these contaminants to detention ponds for necessary treatment. The fate of any spill in DIA's drainage network is likely volatilization, biodegradation, or dilution to negligible concentrations while remaining in the water or adsorbing to soil. In summary, the minute nature of JFS-U25 means that there are no regulatory constraints pertaining to any proposed cleanup and remediation alternatives.

DIA's primary desire is for the new containment and cleanup method to take an equal or lesser amount of time as the current method. Since the individual airlines are responsible for cleaning up spills, it is imperative that the time it takes to do so does not delay scheduled airport operations. As a team, it was decided that time would be a key factor for practicality and feasibility, followed by environmental impacts. Human health was determined to be the final most important criteria to consider. Since the current methods do not pose much of an impact on human health, the goal was to continue to minimize the risk. The final design should not require any extra personal protective equipment, nor should it require increased worker contact with spills. DIA expressed that cost is not a primary concern, and that more emphasis should be placed on remediation, innovation, and expediency.

3.0 Interactions with Airport Operators and Industry Experts

The BEST desired to work with DIA and their outstanding Environmental Program. Occupying more land than any airport in the country, the team felt that there was great potential for improving environmental interactions on a large scale at DIA. The BEST reached out to DIA and began working with Scott Morrissey, the Director of Environmental Programs.

The team created a list of preliminary questions pertaining to everyday airport operations, focusing specifically on the fueling procedures and how fuel is most often spilled. A phone conference was held between the BEST and Mr. Morrissey to determine the basis for the design project. Mr. Morrissey informed the BEST that JFS-U25 are the most common threat to environmental and safety efforts at DIA. Though potentially harmful, these spills are not reported to regulatory agencies. Mr. Morrissey also informed the BEST that DIA is currently using absorbents to collect the spilled fuel. These absorbents include diapers, cat litter, speedy dry, sawdust, and, most commonly, Absorb-All. Based on information from Mr. Morrissey and a review of sample spill reports, it was determined that the median spill sizes encountered at DIA are JFS-U3.

Mr. Morrissey expressed interest in a solution that provides improvements to remediation time, sustainability, and cost. The greatest emphasis was on cleanup time. Mr. Morrissey stated that if it takes an exorbitant amount of time to remediate a spill, airport operations could potentially be delayed and create problems for airlines, workers, and travelers.

With this information, the BEST assembled three designs to further investigate. The team worked diligently on creating deliverables in the form of a proposal and an alternatives assessment. The proposal was constructed to provide Mr. Morrissey with the assurance that the BEST understood DIA's goals and could cater to their needs. The alternatives assessment was written to provide Mr. Morrissey with several designs to review. Alternatives were investigated and screened against one another in a decision matrix approved by Mr. Morrissey. The BEST has continually kept in contact with Mr. Morrissey via phone calls and email to ensure a collaborative approach to the design process. Mr. Morrissey is very satisfied with the progress the team has made and with the final proposed design.

4.0 Team Problem Solving Approach

In order to produce the best possible design for DIA and the FAA, the BEST proposed, investigated, evaluated, and compared three alternative designs for an improved method for the cleanup and containment of jet fuel spills: microbial degradation of hydrocarbons, increased volatilization via infrared light, and oil solidifiers. A literature review of each technology and a brief alternative assessment is provided in this section.

4.1 Microbial Degradation of Hydrocarbons

4.1.1 Literature Review

4.1.1.1 Background

Biodegradation of hydrocarbons through microbial metabolism is a complex process and has been the focus of many scientific studies for the past several decades. The primary system considered in previous research is the remediation efforts of contaminated media. The purpose of this section is to outline and apply the concepts of media and metabolic processes as they apply to microbial degradation of hydrocarbons. These concepts would be applied to remediation of jet fuel spills at DIA through preliminary sizing, standard operating procedures, and cost estimation of a biodegradation system.

4.1.1.2 Media Properties

Hydrocarbon biodegradation occurs in both soil and water, and the differences in the properties of the two media can strongly influence the fate of a microbial population (Leahy, et al., 1990).

Figure 3 Oil film on the surface of rocks

The exact chemical composition of hydrocarbons varies greatly between fuel types and levels of refinement. However, general similarities between most hydrocarbons allow for general application of experimental results across fuels (Leahy, J.G. et. al, 1990). The most common hydrocarbon contamination sources in the United States are USTs, used for automobile gasoline and diesel fuel. Three decades of research in the design of metabolic degradation models for carcinogenic and hazardous fuel constituents has been conducted to aid in the remediation of UST contamination (Leahy, J.G. et. al, 1990). The fuel of interest for this application is Jet A fuel. Like most fuel types, Jet A contains benzene, toluene, ethylbenzene, and xylene (BTEX) compounds. Common polyaromatic hydrocarbons are shown in Figure 4 for reference. To ensure that the degradation models can be applied appropriately, differences in properties between the modeled fuel and the fuel of interest must be investigated (Samanta, et. al, 2002).

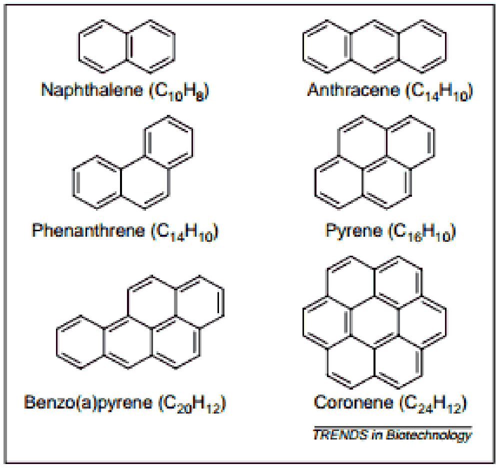

Figure 4 Examples of common polyaromatic hydrocarbons

4.1.1.3 Metabolic Processes

Hydrocarbon degradation occurs due to the biological process known as metabolism. There are three different functions that define this specific metabolism: assimilative biodegradation, intracellular detoxification, and co-metabolism (Johnsen, A.R. et. al, 2004). Assimilative biodegradation is the direct breakdown of a carbon source to yield energy. It is a very common mechanism that is essential for successful degradation. Intracellular detoxification is a biological attempt at making the hydrocarbon more water soluble. This process has been observed to be an initial response before degradation occurs (Johnsen, A.R. et. al, 2004). This function is highly desirable for a community because of its increased ability to degrade hydrocarbons with four or more rings (Samanta, et. al, 2002). Co-metabolism is defined by an enzyme that does not exhibit extreme selectivity (Johnsen, A.R. et. al, 2004). This trait allows similar hydrocarbons to be degraded by a single species of microorganisms. For any fuel biodegradation, co-metabolism is usually the defining parameter of the population. This is because it allows the organisms to access the vast variety of hydrocarbons available and not to be left only with the hazardous aromatic ring constituents.

The evolution of microbial adaptations is largely attributed to prior exposure and selective enrichment (Johnsen, et al., 2004. Samanta, et al., 2002. Leahy, et al., 1990). It has been shown in academic studies that microbes already present in hydrocarbon contaminated areas have much better growth rates compared to those not exposed to those environments. The prior exposure of bacteria theoretically promotes selective enrichment. Selective enrichment is the increase in plasmid DNA that have unique roles in degradation (Leahy, J.G. et. al, 1990). Along with naphthalene, this DNA has been shown to encode metabolism pathways of BTEX compounds. Essentially, the theory states that microbial communities have an adaptive mechanism based on plasmid DNA concentrations which are influenced by the surrounding ecosystem (Leahy et al., 1990).

There are three primary adaptations that function to increase biodegradation through Fick's First Law of diffusion, shown in Figure 5 (Johnsen, et al, 2004):

$$Eq. 1 \ \frac{\mathrm{Q}}{t} = \frac{-\mathrm{DA}(\mathrm{C_o} - \mathrm{C_x})}{x}$$

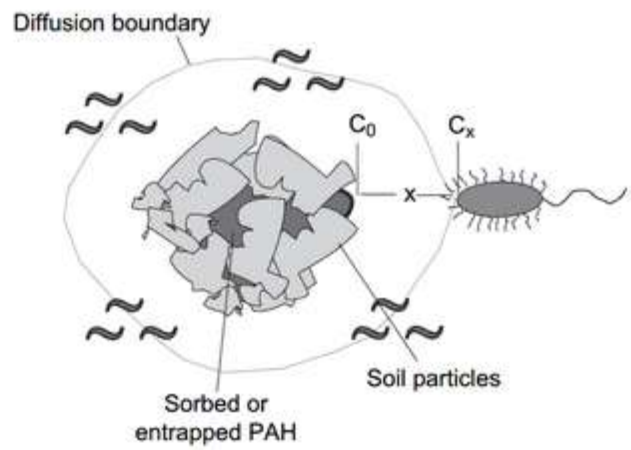

Figure 5 Figure demonstrating Fick's equation. C_0 is the concentration at the membrane, C_x is the concentration near the compound, and x is the diffusion distance.

The first approach to increase diffusion is to increase the surface area, A. Microorganisms have been shown to increase the surface area through excretion of bioemulsifiers and biosurfactants. The next approach is to control the concentration near the compound, C_x. Microorganisms have been able to lower the concentration near their cells to less than the aqueous solubility concentration to match their maximum possible uptake of the nutrient. This has been shown to increase diffusion efficiency. The final mechanism is to decrease the diffusion path length, x. Cells have been shown to create a continuous biofilm over hydrocarbons which significantly decrease the diffusion distance. This also causes an increase in the concentration gradient which further increases the diffusive mass transfer rate (Johnsen, et al., 2004).

4.1.2 Alternative Design

4.1.2.1 Preliminary Sizing

The on-site bioreactor is designed to degrade batches of hydrocarbon fuel that is no more than 30 gallons. Assuming two 8 gallon spills a week, there is less than 500 gallons of fuel to be considered per year. The degradation would use ten to fifteen 55 gallon metal drums for primary degradation with a 7,900 gallon large dumpster for secondary degradation. The purpose of primary degradation is to begin microbial growth in a controlled environment; therefore, the concepts outlined in media properties would be applicable in the 55 gallon drums. The purpose of the secondary degradation in the dumpster is to continue the slower degradation of larger hydrocarbons with four or more rings. The media properties would be less specific, but ideally the adaption concepts would apply here. The dumpster should be able to store waste from small spills over the years. During that time, a microbial population could adapt to degrade the untouched products if any escaped from the primary step. Placement of this infrastructure on DIA property would be discovered based on ease of access, the surrounding buildings, and the underground electrical grid.

4.1.2.2 Cost Estimate

The initial cost of the construction of the facilities and basic equipment will be between $30,000 and $47,000. A part time employee will be required to monitor this facility to ensure degradation is occurring. This estimate did not take into account inflation for recurring costs primarily because this alternative is much more expensive even on a minimalistic basis. The costs are outlined in Table 1, with cost calculations on Appendix G.

Table 1 Microbial bioremediation cost analysis

Item	Unit price	Total
15 x 55 Gallon Drums	$80-$100 (Current Ebay Price)	$1,200 to $1,500
7,900 Gallon Dumpster	$2,500 to $5,000 (Current Ebay Price)	$2,500 to $5,000
Industrial Scale (for drums)	$180 (Current Ebay Price)	$180
Building (1,000 sq-ft) with	$5-8/sq-ft concrete floors (Oldcastle Architectural)	$8,000
9ft high ceilings (1,194 sq-ft) 30’ by 33.3’’	$11.25/sq-ft concrete walls (Oldcastle Architectural)	$13,432
Hvac System	$4,000 to $8,000	$4,000 to $8,000
Heating and Humidifier	$8,000 to 10,000	$8,000 to $10,000
Electricity (Annual)	Summer $55/month Winter $150/month (City Data)	$1,230/year
Microbe Nutrients		$300/year
Maintenance/Operation	$25/hour 20hrs/week	$26000/year
	Total	$30,000 to $47,00 Initial cost and $27,530/year

4.2 Increased Volatilization via Infrared Light

4.2.1 Literature Review

4.2.1.1 Background

Assessment of this alternative investigates the effects of infrared (IR) radiation exposure on the volatilization of Jet A aviation fuel. At present, volatilization of jet fuel spills as a cleanup and remediation technique is not practiced in airport operations. In order to determine if IR could be a viable and efficient remediation option, several parameters of the process were investigated. These parameters included: potential spill surface area, operating temperatures of the fuel, energy transfer from the IR heat source to the fuel, time until complete volatilization, and upfront and maintenance costs.

4.2.1.2 Infrared Lamps

The primary use of IR lamps is to provide heat. This heat can be applied over ranging intensities and surface areas. For example, IR lamps are used extensively in the restaurant business to provide moderate warmth to a large area in outdoor dining areas and also to provide concentrated heat to a small area to keep prepared food warm in kitchens. IR heaters work by emitting long-wave IR radiation as thermal energy.

Several hazards present themselves when dealing with such heaters. Distance from the target area, pressure buildup in the lamps, and careful handling must be considered in the design (Howstuffworks.com, 2014). Two types of infrared heat lamps exist: gas-powered and electric, each with their own benefits and concerns (GoAskAlice, 2012). Gas-powered lamps are extremely heat intensive and may not be appropriate on the tarmac of an airport. Due to these safety concerns, gas-powered IR lamps were omitted from consideration.

For this design, spill cleanup time is of the utmost importance. Our design cannot be positioned in areas of airport operations for significantly more time than is currently required to remediate these spills. To maximize efficiency within given time constraints, this design must heat spills to the maximum safe temperature to increase volatilization rates and minimize cleanup time.

4.2.2 Alternative Design

4.2.2.1 Spill Area

The size of the spill was the first parameter needed to determine the feasibility of IR heaters for remediation purposes. Although JFS-U25 are, by definition, less than 25 gallons, DIA typically deals with JFS-U3, much smaller than JFS-U25 (Morrissey, 2014). As seen in Figure 6 which shows the relationship between circular spill diameters of various sized spill volumes and spill heights, a 0 to 3 gallon spill covers significantly less area than a 25 gallon one. Calculations represented are given in the Table 7, Appendix H. In addition to the parameters used to produce Figure 6, numerous environmental variables can alter the area of a jet fuel spill. These parameters include porosity, absorbency, roughness, slope variation, wind, and others (Hertzberg, 2014). At some point, increased accuracy in spill area prediction will require site-specific experimentation which is outside the scope of this design phase (Hertzberg, 2014). Therefore, assumptions were needed to overcome this on-site surface and environmental variability. Based on experimental data relating liquid free spills to their heights on various surfaces, a height range of 0.6-2.0 mm was investigated for Jet A aviation fuel spills of 0 to 25 gallons, with results shown in Table 7 (Simmons et al., 2003).

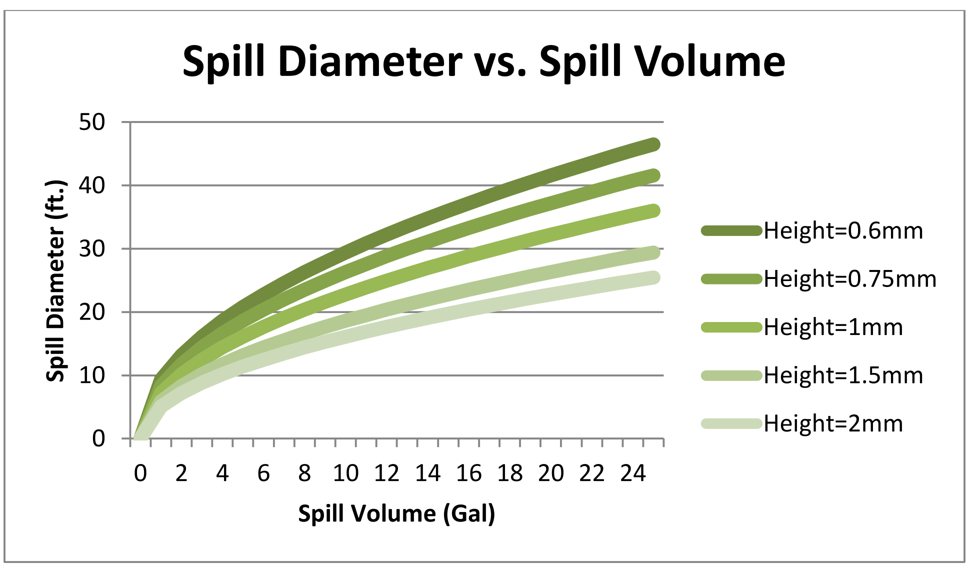

Figure 6 Diameter of the spill based on the volume spilled and the height of the film layer

As shown in Figure 6 spill volumes of JFS-U25 can reach diameters between 25-50 feet, depending on the height and volume of the spill. However, as DIA primarily encounters JFS-U3, maximum spill diameters of 5 to 15 feet will be most commonly seen.

4.2.2.2 Operating Temperatures of Spill

Volatilization of liquids is proportional to temperature. Jet fuel is highly flammable, so a rise in temperature will increase volatilization. However, the associated risks will also increase. In order to minimize cleanup time, it is desirable to heat fuel spills to the maximum safe temperature as rapidly as possible. This process must be confined within safe operating temperatures to minimize ignition or explosion risks. In addition to the parameters discussed, important properties of Jet A are listed in the Material Safety Data Sheet (MSDS).

The flash point of Jet A is 37.8 degrees Celsius. Above this temperature, exposure of the spilled liquid fuel to an ignition source will result in the fuel's combustion. While this ignition potential is an important safety concern for airport workers to remain aware of, there is a negligible chance of any ignition source coming in contact with a fuel spill (Morrissey, 2014). Therefore, this flash point temperature can be safely exceeded during the heating and volatilization process. Above the flash point of Jet A is its boiling point of 175 degrees Celsius and its auto ignition temperature of 210 degrees Celsius. Of these two values, the boiling point is more indicative of the maximum allowable fuel temperature. It should be noted that this figure is likely an overestimate of the actual temperature to which the fuel needs to be heated in order to completely evaporate; because Jet A is highly volatile, it will likely completely evaporate at some point during the heating process before the boiling point is reached. In the event that some of the spill does remain in liquid form once the boiling point is reached, the resultant phase change will volatilize the remaining fuel in a minimal period of time.

The lower temperature bound of the operating zone is highly variable, depending on multiple environmental conditions. For the purpose of this preliminary design, a minimum temperature of 0 degrees Celsius serves as the design parameter. This is likely an underestimate of the minimum fuel temperature encountered under most operating conditions, as fuel is likely stored and dispensed at higher temperatures. However, lowering this bound results in greater certainty that actual performance will exceed that predicted by this preliminary design.

4.2.2.3 Energy Transfer

Precise and accurate modeling of the relationship between the amount of energy released by the IR lamp and the amount absorbed by the spill is a complex and variable process. For the purposes of this preliminary design, several assumptions have been made to simplify this prediction. Upon continuation of this design, these assumptions should be replaced by more detailed approaches.

The first assumption is that all of the energy output from an IR bulb reaches the spill. In reality, a portion of the heat released will be lost to the environment during heat transfer through the atmosphere, increasing spill volatilization time. This heat loss will increase with the distance between the spill and the lamp and with decreasing atmospheric temperature. However, preliminary design suggests that the distance between the heat source and most spills will be between 3 and 9 feet, a distance comparable to many IR heating applications. In addition, the effect of low atmospheric temperatures on heat loss may be partially buffered by the previous assumption of an underestimated lower spill temperature boundary.

The second assumption is that the energy reaching the surface of the spill is absorbed in its entirety. In actuality, temperature gradients, fuel absorptivity properties, and other variables play a role in decreasing the absorption of energy by the spill, increasing the time to complete volatilization. Again, additional assumptions contributing to an overestimate of volatilization time will likely be mitigated by this underestimate.

A final assumption is that no heat transfer between the spill liquid and underlying concrete takes place. This interaction is highly variable, as concrete and fuel temperatures are both environmentally dependent.

4.2.2.4 Volatilization Time

To generate a figure indicating the time until complete volatilization, one additional assumption is implemented. In reality, complex volatilization kinetics play a role in determining the rates at which various components of jet fuel will evaporate. For the purposes of this preliminary design, these volatilization kinetics are neglected, and a simplified approach is used. Furthering this design, it is likely that this simplification would be replaced by a stagnant film boundary layer model (Ryan, 2014).

For a sample calculation, a realistic power output figure of 18,000 Watts was used. To achieve this, 3-6,000 Watt bulbs will be used in series. A 6,000 Watt configuration is shown in Figure 7. IR bulbs and configurations are available in a wide range of power outputs above and below this figure. Input parameters used in the calculation of a sample 3 gallon spill are shown in Appendix H, Table 8.

Figure 7 6000W IR bulb configuration (SOLARIA Alpha Series, 2014)

The estimated 3 minute time to complete volatilization is comparable to that of current cleanup processes at DIA, making IR evaporation a highly competitive alternative.

4.2.2.5 Advantages

In addition to rapid cleanup time, many advantages are linked to IR remediation which could greatly improve airport environmental interactions. The design will be able to handle JFS-U25 of most sizes and on all terrains while leaving virtually no residual fuel or materials behind. After initial purchase, there will be no continuous consumption expenses as seen with the restocking of absorbents.

Sustainability could also see immediate improvements to the already excellent standards at DIA. The volatilization of the fuel into the atmosphere will have the same fate as current processes where the absorbed fuel is ultimately evaporated. However, the absence of off-site transport will reduce unnecessary carbon emissions and disposal costs. This lack of handling of the absorbent also decreases direct contact to workers and will therefore reduce their exposure time to toxic chemicals. The potential to move to renewable energy to power the lamps will always be an option, though increased initial investments would be inevitable.

It is believed that there will be no serious non-technical issues regarding the acceptance of implementation. IR is perceived as a more innovative solution to remediation and workers should have no problem using a device that will do their work quickly, cleanly, and effortlessly.

4.2.2.6 Disadvantages

While advantages seem abundant, several important disadvantages may arise and must be specified. Though minute compared to other remediation options, DIA will see a larger upfront cost when switching to IR than if they kept to their current methods. There are also higher chances of mechanical or electrical malfunctions that would require a backup solution. Malfunctions will of course increase maintenance costs and could potentially result in increased lifetime expenses.

The transport of the lamps to the contamination zone could also increase the overall cleanup time. The variability of heat flux due to environmental conditions (solar radiation, surface temperature, snow, wind, etc.) can also affect volatilization times immensely—so much so that it is difficult to model exact circumstances. Therefore while IR is expected to be a very effective means of remediation, certain environmental conditions can decrease its efficiency. In addition, there is a high degree of uncertainty in an open system like the proposed IR evaporator. Health and safety precautions surrounding flammable fumes and the lower explosive limit of volatilized Jet A may be of concern. Finally, while the dilution of the volatilized fumes into the atmospheric sink may result in negligible amounts of pollution, IR evaporation still presents public perception challenges with regard to environmental impact and atmospheric pollution.

4.2.2.7 Cost Estimate

The capital cost of the IR design is $4,500 and is outlined in Table 2. The total cost is $6,557 and is outlined in Table 3.

Table 2 Capital cost of IR design

Design Component	Capital Costs
Lamps	$3,300
Portable Generator/Battery	$900
Transport Mechanism	$300
Total Capital Cost	**$4,500**

Table 3 Total cost of IR design

Operations and Management	Total Costs
Annual O&M	$121
Present Value O&M	$2,057
Capital	$4,500
Total Present Value Cost	**$6,557**

4.3 Solidifiers

4.3.1 Literature Review

4.3.1.1 Background

Solidifiers are mixtures of compounds which bind to hydrocarbons to form a solidified product (Oil Solidifiers, 2014). Three types of solidifiers exist, all with their individual advantages and disadvantages. The first, polymer sorbents (Fingas, 2008), are typically composed of styrene butadiene and capture hydrocarbons through adsorption onto a polymer (Mohanraj, 2010) as shown in Figure 8. The final product is held together only by weak van der Waals forces; there are no chemical reactions. Polymer sorbents are advantageous due to their low toxicity, excellent mixability with hydrocarbons, and low adhesion to foreign objects. However, when used in water, the polymers form a crust around the hydrocarbon that limits complete solidification. In this case, if pressure is applied to the solidified product, the liquid can be re-released (Fingas, 2008). Because DIA will only be dealing with terrestrial spills and will be physically mixing the solidifier into the fuel, these negative attributes should not adversely affect effectiveness.

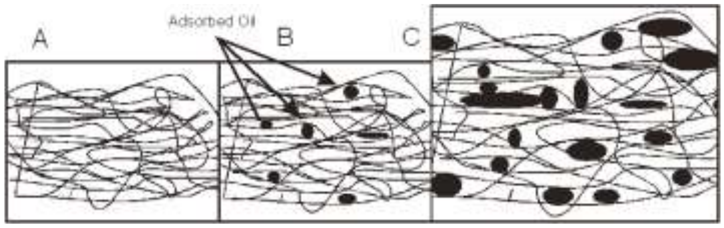

Figure 8 An example of polymeric absorption, showing expansion of the polymer after indtoduction of oil (Fingas, 2008)

The second form of solidifiers, cross-linking agents (Fingas, 2008), often include norbornene and anhydrides (Mohanraj, 2010) which chemically bind with the hydrocarbon to create a stable product. Figure 9 shows the reaction taking place. The final result is a completely solidified product with no leakage under pressure. However, in some circumstances, the chemical reaction that occurs may further react with other nearby compounds in the region and form unwanted byproducts (Fingas, 2008).

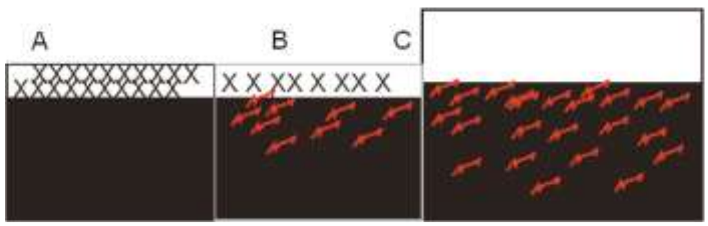

Figure 9 Cross-Linking Agent schematic showing the solidifying ingredient as X's, the oil as black, and the red stitches as the cross-linked combination (Fingas, 2008)

The last group of solidifiers, combination agents, is a combination of polymer sorbents and cross-linking agents (Fingas, 2008). Figure 10 shows the process of Combination Agents. The effects of both solidifiers are present—the combination of the adsorption to the hydrocarbon and the chemical reactions has the ability to form a more stable solid. Because of the two mechanisms occurring simultaneously, this solidifier achieves better overall solidification. The possibility of the formation of an exterior crust is present as it is for polymer sorbents. However, as is the case with polymer sorbents, this should not be a factor in the effectiveness of the product.

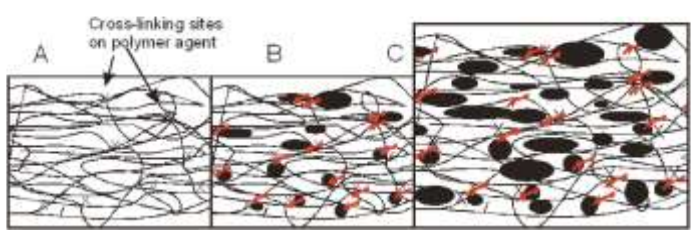

Figure 10 Combination Agents adsorbing to oil while also cross-linking to various components (Fingas, 2008)

4.3.1.2 Solidifier Life Cycle

Currently, solidified oil is being reused in the asphalt industry to add elasticity (Mohanraj, 2010). This is a viable option upon remediation and may prove to be a marked alternative advantage during environmental and cost analyses. As previously stated, polymer sorbents are typically made from styrene butadiene (Mohanraj, 2010), a synthetic plastic used in the production of automobile tires (Solution Styrene-Butadiene Rubber (S-SBR), 2012). Automobile tires have a limited lifetime, so waste from this industry is constant and plentiful. The tires are currently being recycled to make "crumb rubber" used in asphalt, sport turfs, and in playgrounds (Crumb Rubber, 2014) and can be seen in Figure 11. In addition to the current uses for crumb rubber, it is widely believed that it can be an effective polymer sorbent solidifier. Styrene butadiene swells in the presence of hydrocarbons (Styrene-Butadiene Rubber (SBR), 2014) because it has poor chemical resistance to them (Rubber Material Selection Guide: SBR or Styrene Butadiene, 2005). According to the MSDS, crumb rubber is nontoxic, making the handling and transport of it an easy and safe task.

Figure 11 Crumb rubber size in comparison to a quarter (DeerPath Recyclers, 2014)

4.3.2 Alternative Design

4.3.2.1 Feasibility

Crumb rubber is sold commercially for use in synthetic sports fields, so acquisition is feasible in many locations (Crumb Rubber, 2014). In the subsequent phase of the design, it will be essential to find an industry that will take the solidified hydrocarbon, such as asphalt production. If a company cannot be found that will use the solidified product, it will be treated as waste which will be no different than the currently implemented methods. Because solidifiers are effective for treating any hydrocarbon spill (including diesel, gasoline, and various jet fuels), this design also has the potential to absorb to other spills at the airport.

4.3.2.2 Cost Estimate

The potential for cost savings in switching to crumb rubber from standard absorbent is significant. Crumb Rubber Manufacturers, located in Mesa, Arizona, offers crumb rubber for $0.15 per pound. Other absorbents potentially used by DIA include kitty litter, speedy dry, and sawdust. According to Amazon.com, kitty litter costs approximately $0.50 per pound, speedy dry is approximately $1.25 per pound, and sawdust is around $2 per pound. As shown in Table 4, the raw cost for crumb rubber is significantly less than the price for other commonly used absorbents. Because the method for cleaning up the spilled jet fuel will be the same as the current method, the only change in cost would be the difference in materials. Cost calculations are outlined in Appendix G.

Table 4 Cost analysis of absorbents

Item	Unit Price per pound (USD)	Price for 2550 lbs of absorbent
Crumb rubber	$0.15	$382.50
Kitty Litter	$0.50	$1275
Speedy Dry	$1.25	$3187.50
Sawdust	$2.00	$5100

There will be no additional cost in regards to Operations and Management. In the future, there is the potential for a higher cost if the spent solidifiers need to be transported long distances to be converted into asphalt. The cost for transportation; however, should not exceed the cost that DIA is spending on landfill costs for their current absorbent method and there is the chance that a partnering asphalt facility can fund these transportation costs.

4.4 Screening of Alternatives

To compare and contrast the remaining three alternatives, a decision matrix based on the FAA competition evaluation criteria and Mr. Morrissey's requests was created. The three categories in this matrix are risk to human health, practicality or feasibility, and innovation. These sections were weighted based on their relative point assignments in the evaluation criteria and then graded on a scale of zero to ten, with ten being the most desirable score. Each alternative was presented and evaluated through a discussion process until all BEST members reached a consensus for each score. The matrix is shown in Table 5.

Table 5 Weighted decision matrix

		Infrared		Biodegradation		Solidifier	
	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Risk to Human Health	**8**	3	**24**	8.5	**68**	8.5	**68**
Practicality/Feasibility	**20**						
Time	10	8	**80**	5	**50**	5	**50**
Cost	5	3	**15**	0	**0**	8	**40**
Real World Impact/ Environmental	5	8	**40**	7	**35**	9	**45**
Innovation	**14**	9	**126**	7.5	**105**	**9**	**126**
TOTAL	**420 points possible**		**285**		**258**		**329**

As evidenced in Table 5, the screening process indicated that hydrocarbon solidifiers exhibited the greatest potential for continued development. The BEST proceeded with further investigation and design of this alternative.

5.0 Technical Aspects of Proposed Design

5.1 Crumb Rubber as a Solidifier

In the United States, Americans recycle 233 million tires out of the 290 million used (Kiger, 2012). Currently, there is a large market for the reuse of these tires in asphalt, railroad ties, and playgrounds. An emerging market involves the use of pulverized recycled crumb rubber as a hydrocarbon fuel solidifier. The BEST investigated the solidifying process, the primary solidifying component of used tires, and how a crumb rubber fuel solidifier might be implemented at DIA.

Solidifying spilt jet fuel simplifies the containment, transport, and disposal processes involved with fuel spills. A solid product is more easily handled and transported than a liquid. A solidifier uses a crosslinking agent to bond to the oil and create an internal structure (Ghlalmbor, 2004).

For a single spill, ideal solidifiers create a hardened, single structure. In reality, a perfect solidified structure is not generally feasible, but reasonable stability can be achieved.

Styrene butadiene rubber (SBR) is the principle component in tires which acts as the primary solidifying agent in powdered crumb rubber. It is a synthetic rubber developed during the late 1920's to provide alternative rubber for military needs (Britannica, 2014). The SBR composition of individual tires is roughly 60% of the total rubber components (Ghlalmbor, 2004). This presence of SBR as the majority component in crumb rubber is expected to satisfy absorbent requirements for hydrocarbon fuel spills.

5.2 Crumb Rubber in Asphalt Production

In addition to potential use as an oil absorbent, crumb rubber from recycled tires can also be used in asphalt production. Crumb rubber modifier (CRM) technology includes any use of crumb rubber from discarded tires in asphalt paving materials (Heitzman, 1992). There are innumerable asphalt products and production processes, many of which readily accommodate CRM technology (Heitzman, 1992). A number of the asphalt production processes incorporating CRM technology involve drying, heating, or melting of the influent crumb rubber to temperature greater than 400 degrees Fahrenheit (Aggregate, 2009).

Further research into the temperatures and processes involved in implementing CRM technology into asphalt production led the BEST to believe procedures existing in many asphalt production processes could be harnessed to safely volatilize absorbed hydrocarbons out of contaminated crumb rubber sorbent and regenerate the crumb rubber to be used in asphalt production.

5.3 Twice Repurposed Crumb Rubber as a Jet Fuel Solidifier

The BEST is pleased to propose *Twice Repurposed Crumb Rubber as a Jet Fuel Solidifier* as an improved method for the containment and cleanup of fuel spills at DIA. This design is the product of extensive research into multiple design alternatives and continued client consultation. The BEST is confident in presenting a method competitive with those currently practiced at DIA. It should be noted that while the BEST has designed this method while working closely with

DIA, implementation may be achieved at many other airports across the country. In an effort to keep this design as universally applicable as possible, BEST has intentionally excluded mention of specific crumb rubber suppliers and asphalt production plants in the Denver area. In this way, airports are free to form their own partnerships with local crumb rubber and asphalt producers. In addition, mention of specific quantities and proportions of jet fuel, crumb rubber, and asphalt have also been excluded due to the varying methods of asphalt production. These figures are highly variable with both time and location, and this flexibility allows for manipulation of the design to best serve the client under a variety of conditions. The diagram for the proposed design can be seen in Figure 12.

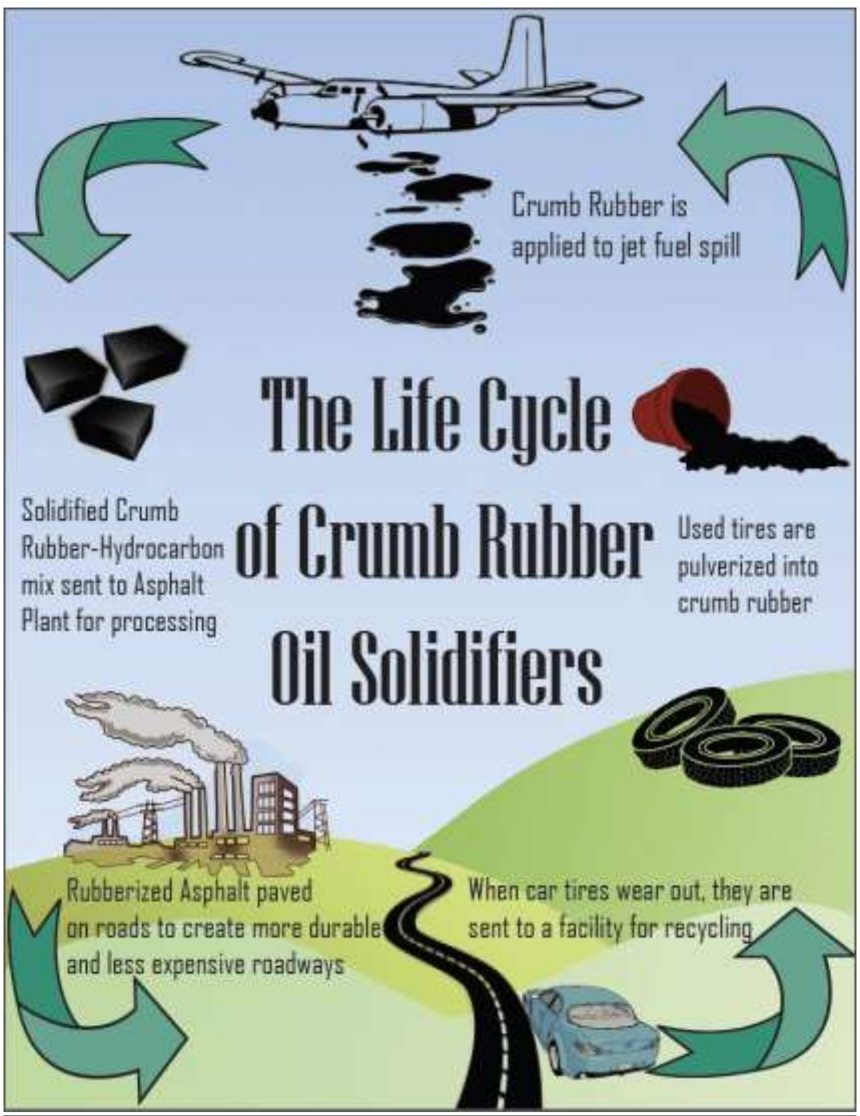

Figure 12 Proposed design flow chart

Transition to the use of crumb rubber as a spill absorbent at DIA could be rapid and minimal, for the process utilizes much of the existing spill response infrastructure at DIA. Crumb rubber can be stored in the same containers as the current absorbent, and the application and removal procedures are nearly identical. This means that all personnel engaging in JFS-U25 spill response will likely be able to continue their work with no additional training. The only notable changes are those involving supply and disposal, and these are minimal at most. Crumb rubber made from recycled tires is widely available, so DIA could choose between a number of reputable suppliers within the area. Current disposal procedures involve the transport of contaminated absorbent to a central location where it is either sent to a landfill or stored with various hazardous wastes until a contracted hazardous waste disposal service picks it up and transports it off site. The implementation of crumb rubber eliminates the need for landfill or hazardous waste disposal fees; the airport will simply need to arrange for the transport of the contaminated absorbent to a partnering asphalt production facility.

Once delivered to the asphalt production facility, operators may implement contaminated crumb rubber into their production procedures as they see fit. As discussed in Section 5.2 Crumb Rubber in Asphalt Production, contaminated crumb rubber will need to pass through the dryer where the hydrocarbons can be volatilized out. In most scenarios, it is likely that the quantity of the contaminated crumb rubber and the volatilized jet fuel will be negligible in proportion to the pure rubber and other hydrocarbon fumes present in the dryer, and will not require any additional treatment to avoid safety and regulatory restrictions (Hernandez, 2014) (Silverstein, 2014). However, the BEST is committed to due diligence with respect to environmental and health and safety concerns, so on-site dilution of the contaminated crumb rubber with non-contaminated product is recommended. In addition, the utilization of a flare to completely combust any residual hydrocarbon vapor or more frequent cleaning of fabric filters in hot mix asphalt plants is recommended for any process involving the possible volatilization of jet fuel from the crumb rubber. Certain asphalt production processes may already implement the use of flares to burn of excess flammable vapors, so installation of new flares may not be required at the facilities (Silverstein, 2014). In the case of a production facility which does not already utilize flares, installation is generally feasible and could be financed by the partnering airport (Silverstein, 2014). During the drying process, expected volatilization of hydrocarbons from the crumb rubber is upwards of 90% (Silverstein, 2014). After this fuel has been volatilized, the regenerated crumb rubber can be used with no restrictions. More information on recommended safety procedures at the asphalt plants can be found in Section 5.4 Safety Considerations.

The BEST suggests that the airport finance this flare installation, as well as the transport of the crumb rubber to the asphalt production facility, because the amount of crumb rubber delivered is likely negligible to the amount required under normal operating conditions, so asphalt producers have little economic incentive to accept airport waste or adapt their facilities to accommodate it (Hernandez, 2014) (Silverstein, 2014). However, if airports are willing to accept the one-time cost of adapting a partner asphalt facility in lieu of continually paying for hazardous waste disposal costs in order to utilize their existing process, the airport may be able to benefit economically and both parties will benefit from the ability to market themselves as more sustainable and environmentally responsible. Financial analysis of this flare installation is not considered in the scope of this design due to the variability of asphalt production processes in and around the Denver area.

5.4 Safety Considerations

The risks associated with jet fuel include vapor toxicity and explosion (Ghlalmbor, 2004). While solidified hydrocarbons do decrease some volatilization, jet fuel is extremely volatile under normal atmospheric conditions and, because it is used in jet aircraft, it has a high internal energy (Fingas et al, 2008). Jet fuel contains nearly 128,000 BTU per pound, 14,000 BTU greater than standard gasoline. This considerably great internal energy leads to a dangerous explosive force when exposed to an ignition source. Jet fuel is a complex mixture of hydrocarbons with molecular structures ranging from C_9 to C_{16} (Ghlalmbor, 2004). Toxic substituents such as BTEX compounds can exist in concentrations lower than five percent of the total mass of the fuel; however, this small concentration still presents a significant health danger for inhalation (Environmental Guidelines, 2012).

Several federal safety documents aim to outline storage, transportation, and operating procedure risks at airports. The FAA’s Safety Management System outlines and explores the implementation of new projects. For this design, the cleanup process is equivalent to those outlined in section ES-301-5.02 for Spill Response of DIA's environmental guidelines. DIA's current cleanup method has a decision making process to be executed when responding to a spill (Environmental Guidelines, 2012). For this design, the operator will determine the volume of the spill and will immediately contact the DIA Communications Center. Nearby operators will assist with containment procedures and will add crumb rubber until solidification occurs and the product is collected and stored. All operators will be required to understand all critical operating procedures for spill prevention. DIA will continue to provide a number of safety training classes for their employees in order to promote safe and efficient fuel cleanup. DIA's spill response document outlines six specific environmental risks that should be avoided at all times: improper disposal, air emissions, odors, and contamination to soil, surface water and groundwater (Environmental Guidelines, 2012). In the decision matrix presented in Section 4.4 Screening of Alternatives, the BEST addressed these risks in order to select the best possible design.

6.0 Impacts and Findings

The FAA works to enforce pertinent safety and environmental regulations at airports across the county. Human health and safety is intertwined with environmental concerns; one should never be substituted or ignored for the other. The prosed design meets FAA goals by improving the sustainability of jet fuel remediation with no additional impact on worker or civilian safety. Emphasis was placed on designing an improved fuel spill cleanup method with maximum utilization of existing airport infrastructure and minimal disturbance to standard operations. This design can be implemented immediately and will greatly improve the sustainability of cleanup methods at DIA.

6.1 Immediate Impacts

Use of scrap rubber from tires in the production of asphalt is currently a growing topic that is beneficial to both tire manufacturers and asphalt facilities. On April 30th, 2014, "Recycle Florida: 2014" will take place in Clearwater, Florida. (Tire Business, 2014). The event aims to spread awareness and to teach about the emerging research on rubberized asphalt. Both the Florida

Department of Environmental Protection and Bridgestone Americas will be speaking at this conference. As more asphalt plants begin using crumb rubber in their production, more crumb rubber will be required to supply this increasing demand. Figure 13 portrays a rubberized asphalt road being paved.

Figure 13 Rubberized asphalt being applied to a road (Asphalt Photograph, 2014)

The BEST's proposed design aims to capitalize on this emerging market in the most environmentally friendly approach possible. Asphalt plants will need this continuous supply of crumb rubber to meet their production needs and a zero-waste stream can be created by rerouting the crumb rubber through DIA without any impacts to workers or operations.

6.2 Long-term Impacts

World tire demand is expected to rise 4.3% annually through 2017 (PRWeb, 2014). Until engineers create an alternative to the rubber tire, there should be a continuous supply of used tires and crumb rubber for DIA to utilize, as seen in Figure 14.

Figure 14 Disposed tires (Tire Pile Photograph, 2014)

The asphalt industry suffered severe economic losses in the 2008 financial crisis (Industry Market Trends, 2013). With a decrease in construction, the rates of new roadways and houses declined (Industry Market Trends, 2013). As the economy resurges, the asphalt industry should recover and expand. The combination of increased asphalt demand with the knowledge of the benefits of rubberized asphalt should lead to more crumb rubber in asphalt production than ever before. Based on these assumptions, there is little doubt that DIA will be able to depend on this reliable outlet to the asphalt plants. Consequently, no foreseeable impacts arise to current DIA operations nor to the viability of this design into the future.

There are no foreseeable long-term impacts associated with implementation of this design. There are minimal differences between the application of crumb rubber and the application of absorbents to fuel spills. DIA will continue using absorbents well into the future unless they find significant economic, environmental, or performance improvements. This design aims to improve all three of these categories.

6.3 Commercial Potential

One distinct advantage of this design is its potential for immediate implementation. According to Scott Morrissey (2014), remediation processes are unfit for implementation if they delay normal aircraft operations:

"*We can't ask an airline to delay [an] aircraft to the gate if the process takes 20 minutes.*"

-Scott Morrissey, 2014

The BEST put this criterion at the forefront of their decision matrix, as seen in Section 4.4 Screening of Alternatives. Necessary steps to seek implementation are not demanding and can be taken immediately. DIA must partner with a crumb rubber supplier and an asphalt plant to deliver the final product. The following three sections aim to further explain how these criteria are met to increase its commercial potential.

6.4 Economic Potential

Three components of this design were investigated to determine its economic benefits by weighing them against current processes: purchasing the crumb rubber, transporting the crumb rubber to the asphalt facility, and potential research. It was assumed that worker salary and other standard operating costs could be neglected due to a similar procedure plan to current remediation methods.

Commercially available crumb rubber can be sold by the pound to consumers for $0.15 per pound or in bulk, typically for synthetic sports turf. TJB Inc. sells a 2,000-pound bag of crumb rubber (nearly 530 gallons) for $459.98 (TJB-INC, 2014). This crumb rubber is made from 100% recycled tires and can be used in hot mix asphalt plants. In comparison, DIA's most commonly used absorbent, Absorb-All, sells for $280 per 55-gallon drum (Absorb-All, 2014). Assuming DIA does not receive a significant bulk discount, the crumb rubber will be 5.83 times less expensive than current methods. Calculations for implementation can be found in Appendix G.

According to Mr. Morrissey, Colorado landfill costs are generally less than extended transport costs, so absorbents may be less expensive to transfer to an off-site landfill than the crumb rubber to an asphalt plant (Morrissey, 2014). In a 2014 estimate by Forbes, Denver is estimated to be the sixth fast growing city in the nation based on population and economic growth (Harden, 2014). With this assessment, it can be expected that with the growth in the economy and population, more infrastructure will be put into place and therefore there will be a greater need for asphalt production. Due to the close proximity of DIA to the expanding Denver metro area, transportation costs are assumed for a maximum distance of 25 miles. Estimates of the price of hauling for Denver-based companies are around $200 per haul (Junk-King, 2014). If large spills are remediated or the solidified product is stored until a larger shipment is ready, hauling costs will decrease. The frequency at which solidified crumb rubber is to be hauled off site can be estimated at three shipments per month. There is also the opportunity to partner with an asphalt plant that assists DIA with the shipment of the product to their site, eliminating or decreasing shipping costs altogether.

Finally, DIA may want to carry out quantitative research to provide an accurate representation of how much crumb rubber is needed to solidify a given sized fuel spill. They will also need to conduct qualitative research to find an appropriate hot mix asphalt production company that can use the solidified product. Neither of these projects are expected take up significant time or resources; however, some time and money should be dedicated to proper validation, not included in the financial analysis. Table summarizes the estimated cost of the implementation of crumb rubber solidifiers at DIA:

Table 6 Crumb rubber implementation cost

Item	Cost	Frequency	Annual Cost
2,000-pounds Crumb Rubber	$459.98	Five/Year	$2,300
Hauling Costs	$200	Three/Month	$7,200
		Total:	$9,500

Based on these calculations, a cost of $9,500/year is expected. This inexpensive annual cost could further decrease if a partnering asphalt plant offers to subsidize or pay for hauling costs.

6.5 Environmental Potential

As shown in the process life cycle diagram in Figure 12, this design is created out of a zero waste concept that diverts one waste stream into a useable product for another, which is in turn used as a component for a third process. This design repurposes unusable tires, prevents the purchase of virgin materials used for absorbents at the airport, and redirects a waste that would otherwise culminate in a landfill to be used in an efficient and practical manner. In essence, this design creates a zero waste way to effectively remove jet fuel spills from airport grounds.

The dryers at hot mix asphalt plants are controlled by fabric filters (EPA, 2000). Ultimately, the fate of the spilled jet fuel from DIA will end up being volatilized in the drying chamber to be captured in the baghouse or combusted in an off-gas flare. If concerns arise at the asphalt facilities over the introduction of foreign hydrocarbons oversaturating the fabric filters, these facilities have the option to increase the cleaning frequency to accommodate the contaminants. Options include pulse jet systems that direct air over the fabric surfaces, shaker systems that physically shake the fabric surfaces, or a reverse air system that shears the fabric surfaces (*What Is a Baghouse?, 2014)*. All are capable of removing contamination to accommodate jet fuel. If for any reason an asphalt facility cannot allow for large quantities to be introduced, they will have the capability of controlling the rate at which the crumb rubber-hydrocarbon mixture enters the dryer. This will allow for smaller quantities and a safer drying process.

6.6 Performance Potential

The performance of the crumb rubber solidifier will need proper testing to ensure solidifying capabilities. SBR is the main solidifying agent in crumb rubber and accounts for 62.1% of the tire's composition, with 31% being carbon black (Takeshi et al., 1999). If 62.1% SBR is not enough to create a fully solidified product, the worst case scenario will result in a thick slurry product that will be comparable to the consistency of current absorbents. The product will still be repurposed at the asphalt facility and used in the same way described in previous sections. The purchasing, application, removal, storage, and transportation of the crumb rubber will all be nearly identical to current processes for DIA, meaning workers will not have to undergo any additional training to accommodate the new design. Therefore, the potential for implementation of *Twice Repurposed Crumb Rubber as a Jet Fuel Solidifier* is extremely high.

6.7 Community Acceptance

All parties involved with this design will benefit greatly. DIA's Environmental Program will know that their remediation procedures have undergone a sustainable renovation that takes into account product life cycle and environmental footprint. Instead of buying virgin materials and discarding to a landfill, they will be buying recycled materials and sending the product to get recycled even further.

Crumb rubber manufacturers will be happy to see this design grow into operation. If this design is implemented at DIA and satisfies their cleanup needs, airports across the country will want to replicate this approach and it will greatly increase the crumb rubber market. The supply of crumb rubber is not at risk because as long as there are automobiles there will be automobile tires and a need to recycle them.

Hot mix asphalt plants will need to allow the introduction of hydrocarbons to their drying process. As previously stated, their fabric filters will do an adequate job of trapping the volatilized or combusted fuel as long as they are frequently cleaned of dust and debris, or off-gas flares can directly combust volatilized fuel. Although different asphalt plants have different regulations and production processes, the BEST is confident that there will be many suitors that will gladly accept cheap, recycled crumb rubber for their asphalt production purposes.

7.0 Conclusion

The proposed design aims to increase the effectiveness of jet fuel cleanup strategies by replacing currently used absorbents for recycled crumb rubber solidifiers applicable to JFS-U25 at DIA. The crumb rubber solidifier will create a more readily transportable product for DIA workers while improving cost, sustainability, and performance. Rather than transporting the spent product to the landfill consistent with current methods, the solidified crumb rubber will be sent to a hot mix asphalt production plant to be processed into highly durable and recycled asphalt.

Final costs of crumb rubber are estimated to be 5.83 times less expensive than current absorbents. Although there may be slightly larger off-site transportation costs due to low Colorado landfill costs, there is a chance for the partnering asphalt plant to subsidize hauling fees in return for a free, usable crumb rubber.

It is with great optimism that successful implementation of this design at DIA will be a catalyst for implementation at airports across the country. Using a recycled product to cleanup fuel spills and recycling it again for practical use is a sustainable model that should be a blueprint for airport environmental interactions into the future.

Appendix A-Contact Information

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Appendix B-Description of the University of Colorado Boulder

The University of Colorado Boulder (UCB) is nestled in the foothills of the Rocky Mountains. Since its establishment in 1876, the university has grown from a modest 44 students to approximately 30,000 undergraduate and graduate students. Eleven colleges provide students with 53 academic departments. UCB is proud of its academic excellence, boasting five Nobel laureates and more than 50 members of prestigious academic academies (About CU-Boulder, 2014). As a research oriented university, UCB is striving to become a model for other universities in regard to comprehensive public research. “By the year 2030, UCB will be one of the nation’s top public research universities and a leading model of the ‘new flagship university’ of the 21st century,” according to the UCB Vision and Mission. The goals of this mission include building a 21st century learning environment, delivering an unrivaled university experience, transforming how they teach, discover, and share knowledge, and more.

UCB is also a leading example for sustainable campus life for other universities and research campuses globally. On April 22, 1970, students established the Environmental Center, a student run and student funded organization that “serves as a catalyst and facilitator for a culture of sustainability at [UCB]” (Mission Statement, 2014). The Environmental Center, more commonly known as the E-Center, has facilitated in gaining recognition for UCB as a sustainable campus by receiving many awards over the years. Most recently, UCB was awarded the EPA Green Power Partnership College & University Green Power Challenge award (Awards, 2014).

The high standard for advancing education and focus on sustainability culminates in the Environmental Engineering (EVEN) department at UCB. The EVEN program branched off from Civil, Chemical, and Mechanical Engineering in 1998, and is relatively new in comparison to other engineering departments (Advising, 2014). It became ABET accredited in 2003, with renewal in 2006 (Advising, 2014). Students in the EVEN program choose from seven options tracks of focus, occasionally combining options or creating their own. Option tracks include energy, water resources and treatment, environmental remediation, chemical processing, applied ecology, air quality, and engineering for developing countries. All students in the EVEN department take the Fundamentals of Engineering exam and therefore gain their Engineer in

Training certificate before graduating, further preparing them to work in the engineering industry.

Appendix C- Description of non-university partners

Denver International Airport

Scott Morrissey is the Director of Environmental Programs for DIA. He was the sole contact we used for information on DIA procedures. Throughout the design process, Mr. Morrissey answered our questions through phone conversations and emails. The preliminary information we received concerned spill frequencies and procedures. He presented us with a number of spill incident reports and assisted us in focusing our design to common small scale fuel spills. After BEST decided on the design constraints and alternatives, Mr. Morrissey gave us his opinions on the alternatives. Finally, Mr. Morrissey gave us useful information on DIA requirements for spill cleanup. This information was included in the decision matrix and strongly influenced our design decision.

Phoenix Industries

Kelly Sockwell is the CEO of Phoenix Industries. Phoenix Industries is an environmental engineering company that focuses of recycling technologies. BEST contacted her requesting a sample of finely shredded crumb rubber to research its use in jet fuel cleanup. She responded quickly requesting a mailing address. The free sample of crumb rubber was received several days later. Although we were not able to design a formal experiment using this crumb rubber, it was helpful to understand the physicality of the product used in our final design.

Jim Stewart, Schmidt Constructions

Jim Stewart is a project manager for Schmidt Constructions. Schmidt Constructions is a diversified road construction, asphalt manufacture, and natural aggregates provider. BEST contacted Mr. Stewart requesting their professional opinion on using asphalt production to incinerate minute quantities of jet fuel.

Appendix E- Evaluation of educational experience

For the students:

1. Did the FAA Design Competition provide a meaningful learning experience for you? Why or why not?

Yes, this competition provided an opportunity to work on a real problem that is being experienced in the field. It gave the team valuable experience working with a client and working through the consulting process.

2. What challenges did you and/or your team encounter in undertaking the Competition? How did you overcome them?

This team was initially comprised of five undergraduates, however one of our teammates dropped the course halfway through the semester, leaving us with unfinished work immediately before a class deadline. We were able to come together in the final hours to complete the deliverable and successfully presented our problem solving approach for the project to the class. Since this incident, the team has contributed more work on an individual basis and we are all proud of the report we have assembled.

3. Describe the process you or your team used for developing your hypothesis.

We developed the hypothesis of the report based on the needs of DIA. After speaking with Mr. Morrissey, we decided that we wanted to strive to find a more cost effective solution to the jet fuel spills occurring on the tarmac. We also wanted to ensure that there was a large environmental benefit, while minimizing the overall effect of the procedure.

4. Was participation by industry in the project appropriate, meaningful and useful? Why or why not?

Yes, the industry professionals we interacted with were very helpful. They provided us with useful data that we would otherwise would not have had access to, i.e. cost figures, and feasibility of implementing our design.

5. What did you learn? Did this project help you with skills and knowledge you need to be successful for entry in the workforce or to pursue further study? Why or why not?

We learned a great deal about the consulting process that occurs in the Engineering field. Since the class was designed to simulate an engineering consulting firm, we had deliverables due along the way that assisted in the final design decision. The process was invaluable to potential work in the future.

For faculty members (Professor Chris Corwin):

l. Describe the value of the educational experience for your student(s) participating in this Competition submission.

The students use this Competition as a vehicle to get real-world experience in working with an actual client (participating airport) on a relevant, current problem. The students develop the project with the client resulting in a proposal, then investigate several alternative solutions to the problem, and finally design the best alternative. The Competition provides the opportunity for the students to combine all their undergraduate courses into this “capstone” project while improving their skills in written and oral communication.

2. Was the learning experience appropriate to the course level or context in which the competition was undertaken?
Yes, very much so.

3. What challenges did the students face and overcome?
Recruiting a participating airport, developing a project scope, and then executing the scope within the confines of a single semester.

4. Would you use this Competition as an educational vehicle in the future? Why or why not?
Yes. The Competition provides a vehicle to motivate the students to perform their best and provides an outlet for their hard work.

5. Are there changes to the Competition that you would suggest for future years?
More assistance in recruiting participating airports. If there were a webpage dedicated to airports that have expressed interest in participating and a brief synopsis of the problem(s) they are facing.

Appendix F-References

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Appendix G- Cost Calculations

Microbial Bioremediation Cost Analysis

Determining cost of heaters:

$$3\ heaters * 1100 \frac{\$}{heater} = \$3{,}300$$

Electricity Costs (O & M Costs): Example

$$12\ kW * 0.5 \frac{hours}{day} * 14 \frac{days}{month} * 12\ months = 1{,}008\ kWh$$

$$1{,}008\ kWh * 12 \frac{cents}{kWh} * \frac{1}{100} \frac{\$}{cents} = 121 \frac{\$}{year}$$

Present Value Sample Calculation:
Current Inflation Rate: 1.6%
Assume: 20 year lifetime

$$P = (A) * \frac{(1+i)^n - 1}{i(1+i)^n} = (121) * \frac{(1+0.016)^{20} - 1}{0.016(1+0.016)^{20}} = \$2{,}057$$

Absorbent and Solidifier Cost Analysis

Assuming the absorbency and weight of these materials are the same as that of Nature's Broom, the following amounts were calculated:

$$\frac{\$3.38}{2\ gallon\ spill} * \frac{20\ lbs}{\$9.95} = 3.40 \frac{lbs\ absorbent}{gallon\ spill}$$

(Nature's Broom, 2014)

Assuming DIA spills 3 gallons 250 times over the course of a year, 750 gallons of fuel are spilled in one year.

$$750\ gallons * \frac{3.40\ lbs}{gallon\ spill} = 2550\ lbs\ of\ absorbent$$

$$2550\ lb * \frac{\$0.15}{lb} Crumb\ rubber = \$382.50\ per\ year$$

Crumb Rubber Implementation Cost Analysis

1) C.R. Calculation: $2000\ lb\ C.R. * \frac{1\ ft^3}{28.4\ lb\ C.R.} = 70.4\ ft^3 = 526.6\ gallons\ for$ \$459.98
    a. *Rubber Crumb, 2014* (for density value of 28.4 lb/cf due to size #2 5-10 mesh)

b. *TJB-INC, 2014* to find cost value

2) Absorb-All Calculation: $280 for 55 gallon drum

a. $\frac{526.6gal}{55gal} = 9.57\ times\ more\ C.R.$

b. $9.57 * \$280 = \$2680$

c. $\frac{\$2680}{\$459.98} = 5.83, so\ Aborb - All\ is\ 5.83\ times\ more\ expensive$

i. Based on *Absorb-All, 2014*

Appendix H- Spill size

Table 7 Spill diameter with varying volumes and film heights

	Height (mm):				
Volume (gal)	0.6	0.75	1	1.5	2
0	0	0	0	0	0
1	9.298672	8.316985	7.20272	5.880997	5.093092
2	13.15031	11.76199	10.18618	8.316985	7.20272
3	16.10577	14.40544	12.47548	10.18618	8.821495
4	18.59734	16.63397	14.40544	11.76199	10.18618
5	20.79246	18.59734	16.10577	13.15031	11.3885
6	22.777	20.37237	17.64299	14.40544	12.47548
7	24.60197	22.00467	19.05661	15.55965	13.47506
8	26.30062	23.52399	20.37237	16.63397	14.40544
9	27.89602	24.95096	21.60816	17.64299	15.27928
10	29.40498	26.30062	22.777	18.59734	16.10577
11	30.84021	27.58432	23.88872	19.50506	16.89188
12	32.21155	28.81088	24.95096	20.37237	17.64299
13	33.52684	29.98732	25.96978	21.20423	18.36341
14	34.79245	31.11931	26.95011	22.00467	19.05661
15	36.0136	32.21155	27.89602	22.777	19.72546
16	37.19469	33.26794	28.81088	23.52399	20.37237
17	38.33941	34.29181	29.69758	24.24797	20.99936
18	39.45092	35.28598	30.55855	24.95096	21.60816
19	40.53197	36.2529	31.39593	25.63467	22.20028
20	41.58493	37.19469	32.21155	26.30062	22.777
21	42.61187	38.11321	33.00701	26.95011	23.33948
22	43.61464	39.01012	33.78375	27.58432	23.88872
23	44.59486	39.88686	34.54303	28.20427	24.42561
24	45.554	40.74474	35.28598	28.81088	24.95096
25	46.49336	41.58493	36.0136	29.40498	25.46546

Table 8 Input parameters for IR calculations

Parameter	Symbol	Value
Volume of spill	V	3 gal
Density of Jet A	ρ	3.053 kg/gal
Heat capacity of Jet A	C_p	2,000 J/(kg*K)
Final desired temperature of Jet A	T_f	175˚C, 448 K (boiling point)
Initial temperature of Jet A spill	T_i	0˚C, 273 K
Energy required to heat spill from T_i to T_f*	E	3,205,582 J
Power output of IR lamp	P	1,800 W
Time to complete volatilization	t_{vol}	3 min