IN-SITU BURNING IN THE MARSHLAND ENVIRONMENT-SOIL TEMPERATURES

by

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Abstract

A series of burns was conducted to evaluate the impact of intentional burning of an oil spill in a marshland environment. Oil spilled in sensitive wetland environments pose unique problems associated with cleanup because mechanical recovery in wetlands may result in more damage to the wetland than the oil itself. *In-situ* burning of oiled wetlands may provide a less damaging alternative than traditional mechanical recovery. Many factors, including plant species, fuel type and load, water level, soil type, burn duration, may influence how well a wetland recovers from an *in-situ* oil burn. Ten burns were conducted in a 6 m tank to expose 80 plant specimens to conditions which were designed to simulate a spill of diesel fuel and the intentional burning of the spilled oil. Plants were positioned at four different elevations, -10 cm, -2 cm, 0 cm and +10 cm, relative to water level. Forty of the plants were instrumented with thermocouples in order to monitor soil temperatures during burns which lasted for either 400 s or 1400 s. The soil temperature data indicate that a 2 cm layer of water should provide sufficient protection to prevent permanent damage to the plant/root system.

1.0 Introduction

Oil spills of crude or refined hydrocarbons in environments such as salt marshes provide unique challenges for oil spill response teams. Typically an oil spill cleanup team may consider allowing the oil to remain in the marshland environment, may consider using chemical dispersants, or may attempt to remove the oil using mechanical recovery methods. If the oil is not removed from the marshland, the toxic properties of crude oil and many refined oil products (Baker, 1970) are likely to kill a majority of the plants within the initial spill boundary. Wind and/or tidal action can spread the oil to additional areas which may include more environmentally sensitive marshlands such as breeding habitats. The oil toxicity and likelihood of the oil spreading usually causes the cleanup team to employ mechanical remediation which often includes the use of heavy equipment such as bulldozers, loaders, and vacuum trucks. Previous researchers (McCauley and Harrel 1981, Wright and Bailey 1982, DeLaune *et al.* 1984, and Kiesling *et al.* 1988) have noted that cleanup attempts involving the use of mechanical reclamation techniques can do more damage to these highly fragile wetland systems than the oil toxicity itself. Obviously, a remediation technique that removes spilled oil from the marsh while causing less damage than mechanical reclamation would be an extremely valuable option for oil spill cleanup teams. A major goal of the oil spill response community, including the Minerals Management Service (MMS) and private oil spill remediation companies, has been to develop cleanup technologies that are less intrusive to the environment.

In-situ burning or intentional burning of spilled oil in wetlands offers the oil spill response community an alternative that may avoid much of the damage caused by mechanical reclamation while still removing most of the oil from the marshland environment and preventing the spread of the oil to environmentally sensitive areas. However, intentional burning of spilled hydrocarbons imposes a fire or thermal stress to the wetland plants which have already been exposed to the chemical toxicity of the oil. The impact of these two stresses, fire and chemical, on plant regrowth and recovery needs to be more fully characterized and understood before *in-situ* burning can be widely implemented as an oil spill remediation technique.

It is not clear which factors control whether marsh burning results in positive or negative impacts to the wetland. Factors which appear to impact wetlands burning and recovery include, but are not limited to, plant species, growth cycle, soil type, soil temperature, fuel chemistry, fuel load, fuel weathering, thermal exposure time, radiation flux intensities, and water levels. For example, if the soil temperatures exceed 60 °C, most plants would suffer permanent damage (Byram 1948, Levitt 1980, and Ahlgren1974), but it not clear what temperatures result from an *in-situ* burn within a marsh. Water levels within the marsh could provide significant protection against the thermal stress of an *in-situ* burn, but it not clear how thick the water layer needs to be to protect the roots from thermal damage. Could the high temperatures resulting from the fire cause the oil to penetrate deeper into the soil as suggested by the work of Kiesling *et al.* (1988)? It is essential that we understand each of these factors if we are to consider *in-situ* burning for the remediation of oil contaminated wetlands.

The overall goal of this study is to characterize and understand the relationship between the fire dynamics of an *in-situ* burn and the ecological impact and recovery of the marshland system. This study exposed eighty sods of *Spartina alterniflora* (soil sections with intact plants) to burning diesel fuel in order to collect data on how the regrowth and recovery of marsh plants are affected by 1) soil, water, and air temperatures, 2) different water levels, 3), levels of thermal exposure (average and peak total heat fluxes) 4) thermal exposure duration, and 5) pre-burn oil exposure. *Spartina alterniflora*, commonly called smooth cordgrass, was selected because this species dominates intertidal salt marshes along the Atlantic and Gulf coasts of the United States. The response and recovery of the plants to an *in-situ* burn is a critical element of this study, but a complete understanding of the impact of *i -situ* burning requires that the plants be observed through at least one growing seas While the regrowth and recovery of the plants will be more fully described in a ,-arate report, this report will focus on how marsh sods were exposed to a series of ten full-scale *in-situ* burns. The report will discuss the soil, air, and water temperatures as well as total heat flux data which was collected during each burn.

2.0 Experimental Apparatus and Procedure

Eighty marsh sods which were harvested by Louisiana State University (LSU) were exposed to the combined chemical and thermal insult which marsh plants would encounter during an *in-situ* oil spill burn in a series of ten experimental burns. For each of the burns, a total of eight sods, four instrumented and four un-instrumented, were positioned at 10 cm, 0 cm, -2 cm and -10 cm relative to the water level. These different water level/ soil elevations were designed to mimic the natural variation in water level /soil heights in a salt marsh. Forty of the specimens were pre-oiled with diesel fuel to simulate exposure to spilled oil before spill response team initiates clean-up. Half of the plant specimens were instrumented with thermocouple arrays which were inserted into the soil in order to monitor soil temperature. Water and air temperature as well as total heat flux above the water surface were also recorded.

In-situ burning of an oil spill in wetlands was simulated by burning a 1.8 cm thick layer of diesel fuel which was floating on water that was 71 cm deep. For each of the 400 s burns, 570 liters (150 gallons) of diesel fuel was added to the surface of the water. A propane torch was used to ignite the diesel fuel and once ignited, it was allowed to burn until the fuel extinguished itself. For each of the 1400 s burns, 570 liters was added for 400 s of burn time and the fuel flow was turned off. The fuel was ignited and the fuel flow was restarted at a rate of 110 liters/minute (30 gallons/minute) which was designed to maintain the fuel layer at a constant 1.8 cm thickness. After approximately 900 s, the diesel fuel flow was turned off and the fuel was allowed to burn until it extinguished itself. Combining the heat of combustion for diesel fuel (No. 2) and the fuel flow rate of 110 liters/minute, results in an estimated heat release rate of about 50 MW. While the target burn durations were 300 s and 1200 s, actual burn exposures were approximately 400 s and 1400 s. The plant specimens were then returned to LSU greenhouses to monitor regrowth and recovery of the plants.

2.1 Round Tank Burn Facility

This burn series was conducted in the 6 m diameter round tank facility at the Fire and Emergency Training Institute at LSU. Within this 74 cm deep tank, eight plant support stands were positioned in a 1.5 m diameter circle (Figures 1 and 2). Each stand supported one of eight potted plant sods at -10 cm , -2 cm, 0 cm and +10 cm relative to the surface of the water. Each burn exposed a pair plants at each elevation, one sod being pre-oiled and the other without pre-oiling. Diesel fuel was introduced over the side of the round tank from an underground supply pipe. A metered pump delivered the diesel fuel at a rate of 110 liters/minute.

2.2 Plant Specimens

One hundred marsh sods (80 sods to burn and 20 sods for controls/spares) were collected from a *Spartina alterniflora* dominated intertidal salt marsh in southeast Louisiana. After collecting a 30 cm diameter and 30 cm deep section, sods were placed into 20 liter (five gallon) containers. Each plant sod was assigned a unique number and were randomly assigned to different elevations, specific burns, and whether or not to be pre-oiled. Phenolic resin coated steel buckets were chosen as plant containers. The resin coating helped reduce the corrosion that would occur as

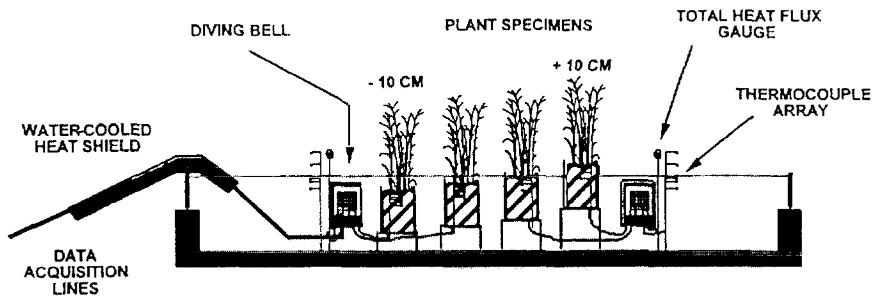

Figure 1. Side View of Round Tank Facility at FETI with Plants Positioned at Different Elevations

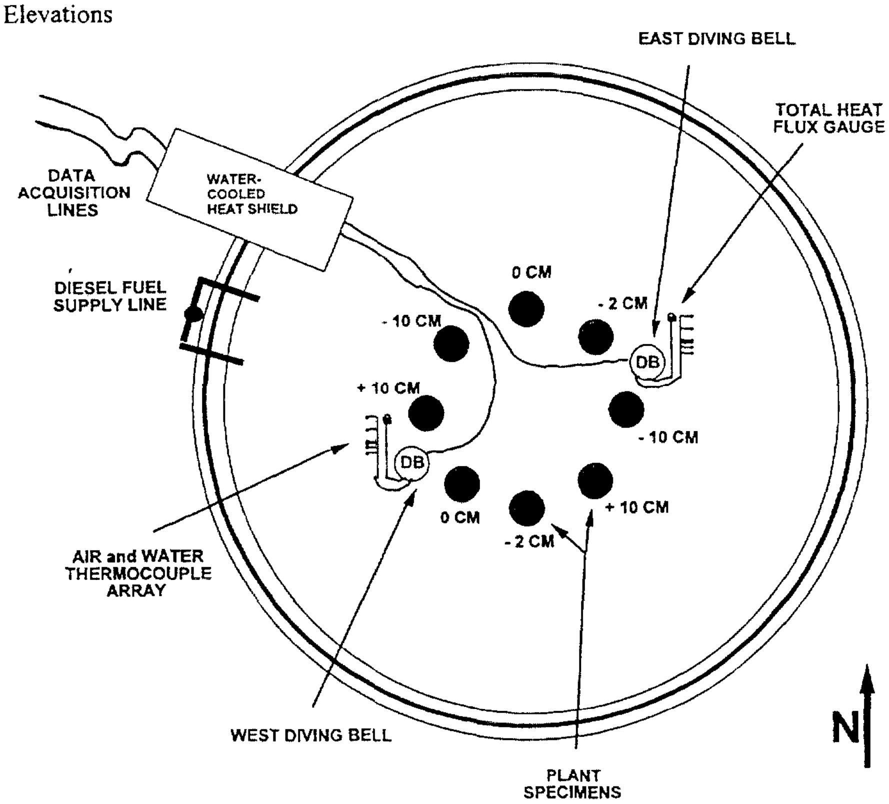

Figure 2. Plan View of Round Tank Facility at FETI with Eight Plants Positioned Around 1.5 m Diameter Circle

each container was filled with brackish sods. Plastic containers could not be used since many of the buckets would be exposed to high temperatures which would have melted or burned the plastic containers. The sods were collected in early July and transferred to the LSU greenhouses.

2.3 Soil Instrumentation

After three weeks of acclimatization in the greenhouse, forty-seven of the plant sods were instrumented with thermocouple arrays in order to track the temperature gradients within the soil. Twenty-three sods were instrumented with the arrays consisting of eight thermocouples while the remaining sods included arrays of four thermocouples. An eight thermocouple array consisted of thermocouples positioned at (0, -0.5, -1, -2, -3, -5, -7, and -10) cm below the soil line while a four thermo-couple array featured thermocouples at (0, -0.5, -2, and -5) cm. Stainless steel sheathed (0.16 cm diameter) grounded Chromel-Alumel* thermocouples were used for the top three positions, (0, -0.5, and -1.0) cm, and top two locations, (0 and -0.5) cm, of each eight and four thermocouple array, respectively. The lower thermo-couples were fabricated using 0.05 cm diameter (24 gauge) Chromel-Alumel wire with FPA Teflon* insulation with a 0.09 cm diameter bead. A slot was cut into each marsh sod and a thermocouple array was inserted down through each sod. After the thermocouples were positioned in the slot, a large pair of flat tined forks were used to close the slot and squeeze the soil around the thermocouples. The soil in all the sods appeared to have a large organic component.

In order to simulate the exposure to spilled oil before the remediation team arrives, forty of the sods were oiled 24 hours before being exposed to *in-situ* burning. Pre-oiling was implemented at the rate of 1 liter/m^2 which resulted in approximately 70 ml of diesel fuel being added to each sod container. Twenty four hours before thermal exposure, the water within the container was increased to a point above the soil and approximately 70 ml of diesel fuel was added to the surface of the water. After the oil dispersed evenly across the water surface, the water level was dropped to approximately 15 cm below the soil surface. After allowing the oil to intermingle with the soil for about eight hours, the water within the sod was returned to the level which existed before oiling was initiated.

2.4 Plant Elevations within the Burn Tank

After arriving at the burn tank, plant sods were arranged in a circle of approximately 1.5 m diameter in order to provide uniform thermal exposure to all plant sods. Each sod was placed on its assigned stand, leveled, and then adjusted to the proper elevation. A "0 cm" sod was placed so that the soil line was at the surface of the water within the burn tank. A "+10 cm" sod was located so the average soil line was 10 cm above the final water level. Average soil level within each marsh sod was obtained by averaging five soil elevations within each container, the highest point, the lowest point, and three other random points. All soil lines were below the rim of the container. The lowest average soil line was 10.5 cm below the rim while the highest soil line was 3 cm below the rim of the container. The average soil line was 6.0 cm with a standard deviation of ± 1.1 cm. For plants which were to be positioned at the 0 cm or -2 cm positions, four access holes, each 1 cm in diameter,

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* Certain trade names and company products are mentioned in the text or identified in an illustration in order to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

were drilled at the water line. These access holes were designed to allow the water in the marsh sod to equilibriate with the water level in the tank.

2.5 Water and Air Temperatures and Total Heat Flux

After positioning and leveling an instrumented plant, the thermocouples were connected to an instrumentation hook-up panel which was located under a "diving bell". Each "diving bell" was simply an inverted 20 liter container which was positioned over the hook-up panel before the burn tank was filled with water. The air captured under the diving bell kept the hook-up panel dry during each burn while the water over the diving bell protected the hook-up panel from the heat of the fire. Each of the two diving bells were connected to the data acquisition system via larger data extension cables which were routed through a water cooled heat shield which was positioned over the lip of the tank wall.

An additional array of seven thermocouples was mounted on the side of each diving bell and monitored the water and air temperatures during each burn (Figure 3). Thermocouples monitored the temperature of air or combustion products at +10 cm and +20 cm above water surface. The water temperature was recorded at (0, - 0.5, -2, -5, and -10) cm. A water-cooled Schmidt-Boelter total heat flux gauge was located near each of the diving bells. Each total heat flux gauge was looking vertically or facing up and was positioned 10 cm above the water surface. Temperatures and total heat fluxes were collected at 5 second intervals using Model CR7 Datalogger (Campbell Scientific, Inc. Logan, UT). Two Weather Pak 400 weather stations (Coastal Climate Co., Seattle, WA) were deployed to record meteorological conditions before, during, and after each burn.

2.6 Post Burn Monitoring

Once the marsh sods were exposed to an *in-situ* burn, the appearance of each plant including exposed thermocouples, condition of soil (standing water, moist, or baked), and presence or absence of plant stubble were documented and photographed. Then all plants were returned to LSU greenhouses and monitored through plant response and soil physico-chemistry. Since the plants were exposed to the diesel fuel and *in-situ* burning during the last two weeks of August 1999, it was necessary to monitor the plants through at least one growth cycle which should occur before April 2000. A more complete description of the methodology used to monitor the plants as well as the results and conclusions will appear in a separate report.

A number of oil and soil samples were collected before exposing the sods to *in-situ* burning and additional samples will be collected throughout the post burn monitoring period. The purpose of the oil chemistry and chemical analysis of these samples will be two fold. First, the chemical analyses will characterize the oil before and after each burn to estimate burn fractions and homogeneity of the plot exposures to the oil. Second, the analyses will be used to assess the exposure of the plant material to soil contamination by the oil residue as a result of physical processes that occur during and after the burn including emulsification, enhanced solubility effects, and water cycling.

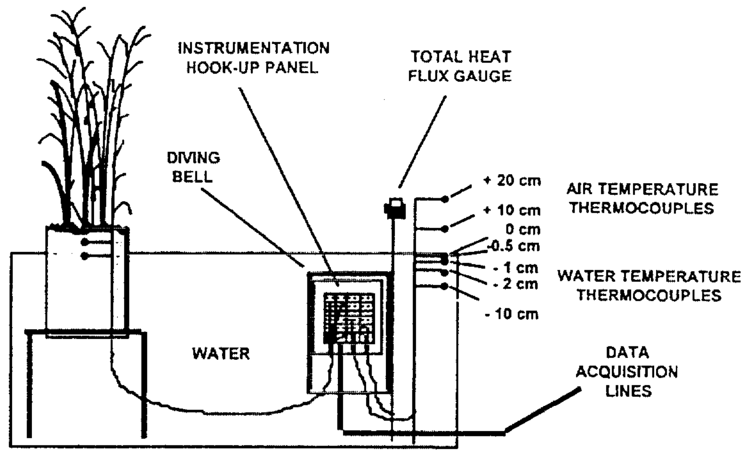

Figure 3. Thermocouple Array for Monitoring Air and Water Temperature, Total Heat Flux Gauge, and Instrumentation Hook-Up Panel

3.0 Results

Soil, water, and air temperatures and total heat flux were graphed versus time for nine of the ten burns. The data set for experiment 5-1 was incomplete due to problems with the data acquisition system. Plant sods will be identified by the elevation of the soil line relative to the water level in the tank or -10 cm, -2 cm, 0 cm, or +10 cm plants. The soil line of a 0 cm plant sod was at the same level as the water in the tank while the soil line of a -10 cm plant was 10 cm below the surface of water. Thermocouples within a plant sod will be identified by the position of the thermocouple relative to the soil line of the plant sod or (0, -0.5, -1, -2, -3, -5, -7, or -10) cm. A 0 cm thermocouple was located at the soil surface of the plant sod and a - 2 cm thermocouple was positioned 2 cm below the soil surface. For plotting purposes, time lines were adjusted for each plot so that 600 s of background data appears and ignition always occurs at 600 s.

For experiment 5-3, soil temperature versus time for each of the four plant elevations, -10 cm, -2 cm, 0 cm, and +10 cm are plotted in Figures 4, 5, 6, and 7, respectively. Each of these four plant sods were pre-oiled. The diesel fuel was ignited at 600 s and burned for approximately 415 s. As these figures demonstrate, peak soil temperatures for -10 cm, -2 cm, 0 cm, and +10 cm sods were 33 °C, 57 °C, 64 °C, and 400 °C, respectively. In sods located at -10 cm, -2 cm, and 0 cm, peak temperatures were recorded after the diesel fuel had extinguished itself. The short burn duration, 415 s, did not appear to be long enough for the temperatures to reach steady state. While the upper thermocouples, 0 cm and -0.5 cm, tended to reach a peak temperature and then begin to decrease rather quickly, the lower thermocouples, -5 cm, -7 cm, and -10 cm, were still increasing slightly nearly 90 minutes after the fuel extinguished itself. The corresponding air and water temperatures

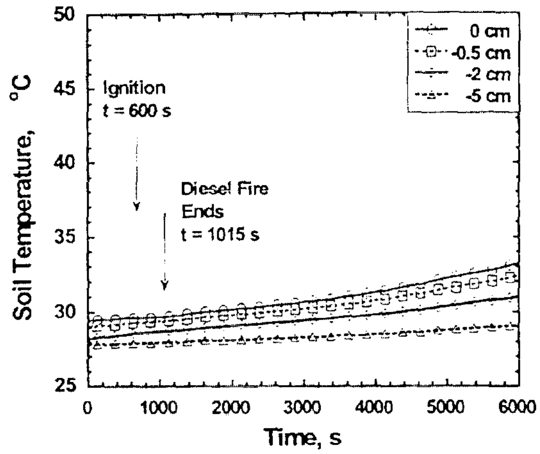

Figure 4. Temperature vs. Time for a 400 s *In-Situ* Burn Exposure with Marsh Sod at -10cm elevation

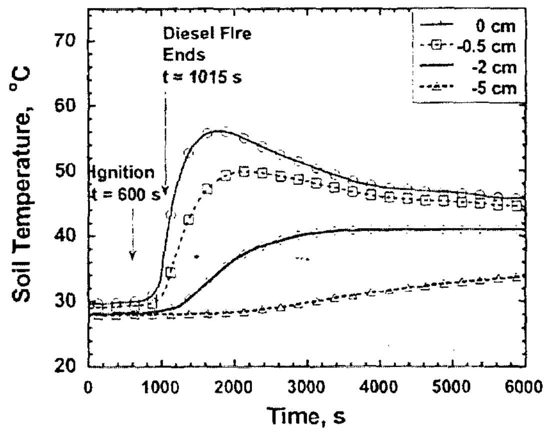

Figure 5. Temperature vs. Time for a 400 s *In-Situ* Burn Exposure with Marsh Sod at -2 cm elevation

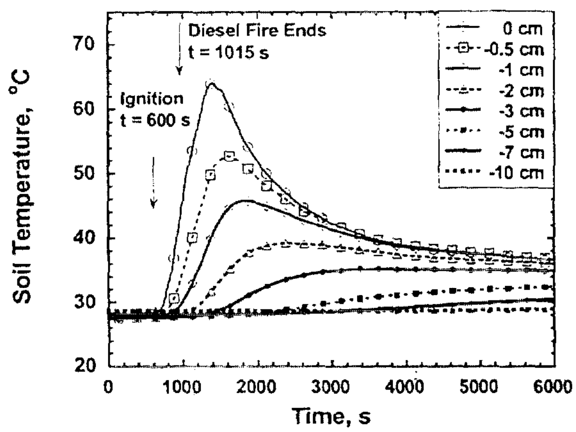

Figure 6. Temperature vs. Time for a 400 s *In-Situ* Burn Exposure with Marsh Sod at 0 cm elevation

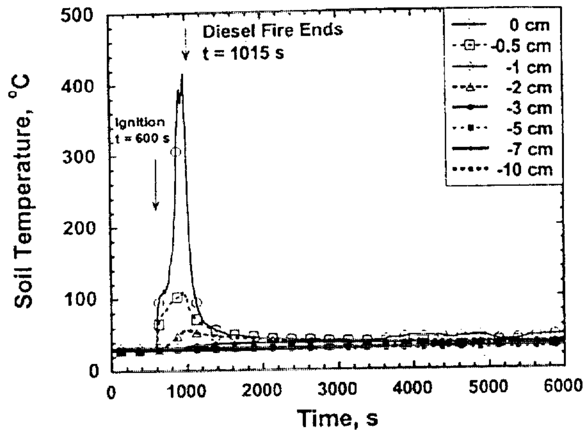

Figure 7. Temperature vs. Time for 400 s *In-Situ* Burn Exposure with Marsh Sod at +10 cm elevation

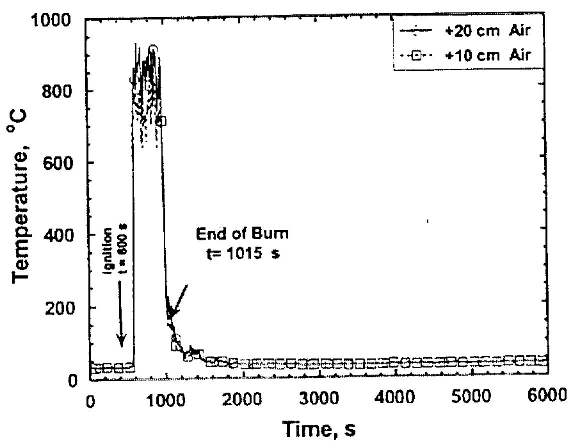

Figure 8. Air Temperature vs. Time for 400 s *In-Situ* Burn Exposure

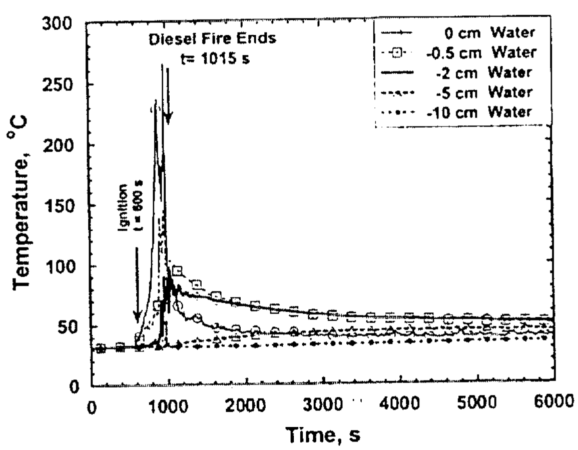

Figure 9. Water Temperature vs.Time for 400 s *In-Situ* Burn Exposure

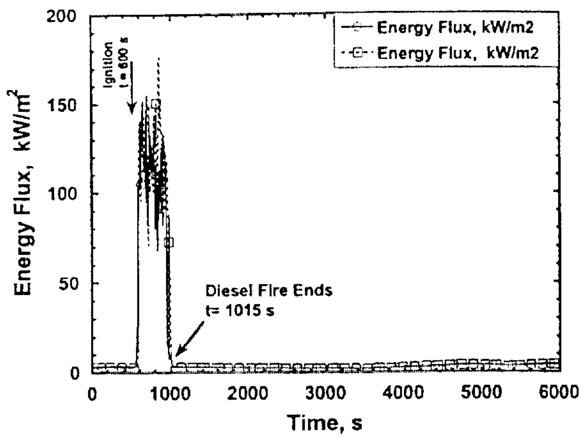

Figure 10. Total Heat Flux vs. Time for 400 s *In-Situ* Burn Exposure

which are plotted in Figures 8 and 9 demonstrate peak temperature of about 900 °C and 230 °C in the air and water, respectively. Water temperatures which are higher than 100 °C suggest that some of the water has been boiled off and the 0 cm water thermocouple was exposed to hot gases just above the surface of the water. The air temperature data reflects the dynamic nature of an *in-situ* burn and it is difficult to ascertain when the thermocouple bead is in a fuel lean, fuel rich or flame zone. Total heat flux data from the West diving bell are plotted in Figure 10 and show peak values of energy flux exceeded 150 kW/m^2 with an average value of 122 kW/m^2.

For experiment 20-5, soil temperature versus time for each of the four sod elevations, -10 cm, -2 cm, 0 cm, and +10 cm are plotted in Figures 11, 12, 13, and 14, respectively. Each of these four marsh sods were not pre-oiled. The diesel fuel was ignited at 600 s and burned for approximately 1395 s. As these figures demonstrate, peak soil temperatures for -10 cm, -2 cm, 0 cm, and +10 cm plants were 40 °C, 58 °C, 85 °C, and 580 °C, respectively. In sods located at -10 cm and -2 cm peak temperatures were recorded after the diesel fuel had extinguished itself. In the sod at 0 cm peak temperature was reached in about 600 s and the value of the temperature then fluctuated between 75 °C and 80 °C. These fluctuations around a temperature of 80 °C suggests the temperature at the soil surface had begun to equilibriate. The peak temperature for the plant at +10 cm did not exhibit the same behavior, however, the peak temperature of almost 600 °C is much closer than the 400 s exposure to the temperature of the air 10 cm above the water surface as shown in Figure 15. Assuming that the soil temperature would not significantly exceed the temperature of the combustion gas product just above the soil, the soil temperatures were beginning to approach steady values. For the +10 cm plant, the temperature of the upper thermocouples, 0 cm, -0.5 cm, -1 cm, and -2 cm, quickly increased to 100 °C and then flattened out. After between 300 s and 800 s of relatively steady temperatures of 100 °C, the temperature then began to increase. This behavior would be consistent with the water in the soil being "cooked" out of the soil. Until most of the water was evaporated out of the soil, the soil temperature remained relatively steady at 100 °C, the boiling temperature of water. After the fire had "dried" out the soil, the soil temperature began to increase for the remainder of the

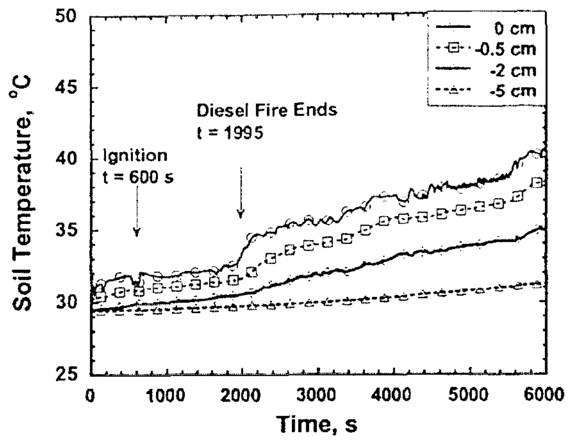

Figure 11. Temperature vs. Time for 1400 s *In-Situ* Burn Exposure with Marsh Sod at -10 cm elevation

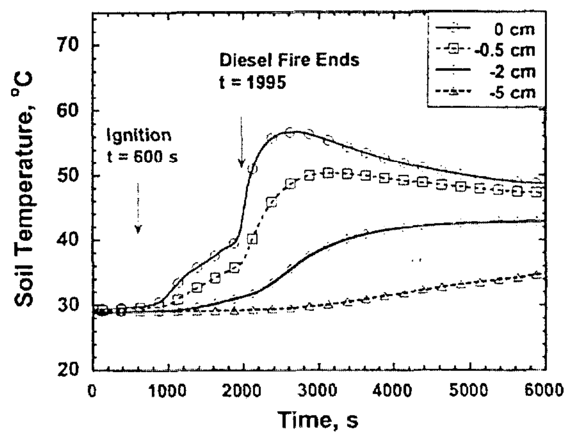

Figure 12. Temperature vs. Time for 1400 s *In-Situ* Burn Exposure with Marsh Sod at -2 cm elevation

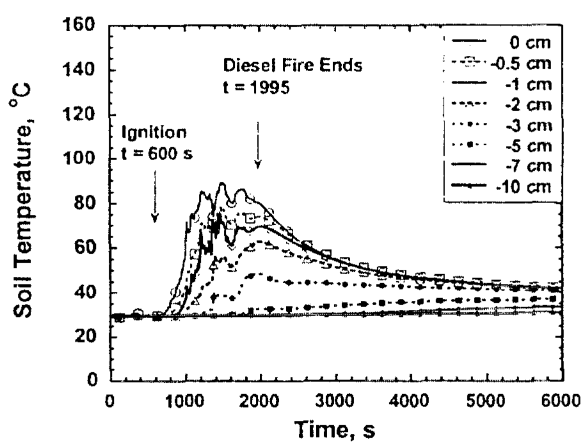

Figure 13. Temperature vs. Time for 1400 s *In-Situ* Burn Exposure with Marsh Sod at 0 cm Elevation

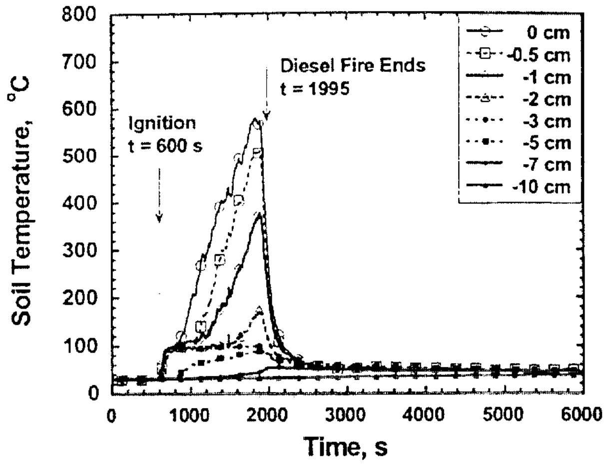

Figure 14. Temperature vs. Time for 1400 s *In-Situ* Burn Exposure with Marsh Sod at +10 cm elevation

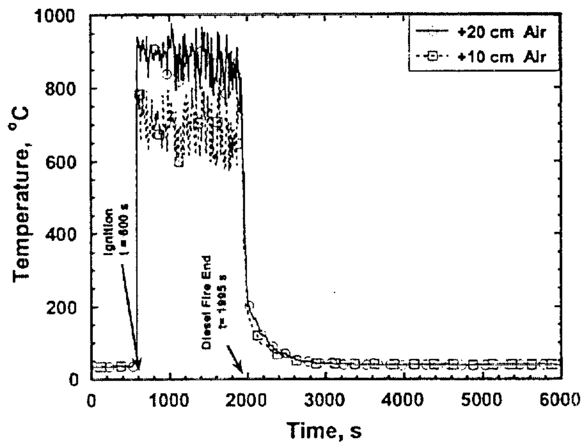

Figure 15. Air Temperature vs. Time for 1400 s *In-Situ* Burn Exposure

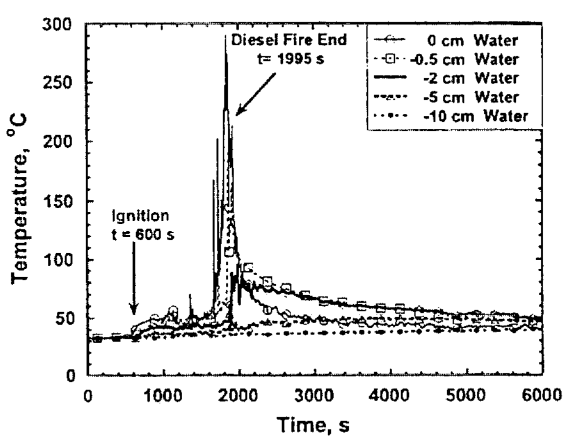

Figure 16. Water Temperature vs. Time for 1400 s *In-Situ* Burn Exposure

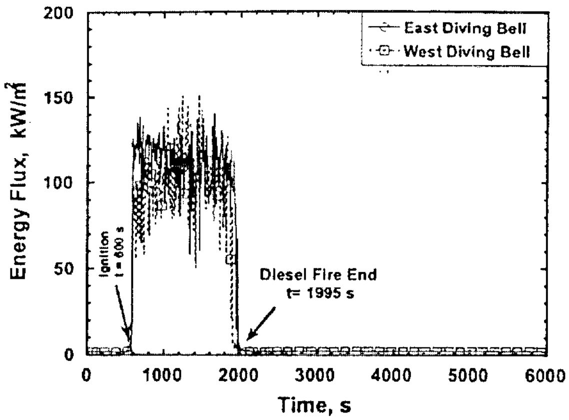

Figure 17. Total Heat Flux vs. Time for a 1400 s *In-Situ* Burn Exposure

fire duration. The corresponding air and water temperatures which are plotted in Figures 15 and 16 demonstrate peak temperature of about 900 °C and 250 °C in the air and water, respectively. Again water temperatures in excess of 100 °C suggest that sufficient water had evaporated to expose the thermocouple which initially was at the surface of the water. Total heat flux is plotted in Figure 17 and shows peak values of energy flux exceeded 130 kW/m^2 with an average value of about 110 kW/m^2.

Peak soil temperatures are tabulated in Table 1 for 400 s and 1400 s burn durations. Average total heat flux values, burn durations, and wind data for each experiment are compiled in Table 2. The estimated depth of the 60 °C isotherm was estimated by observing the highest thermocouple which did not exceed 60 °C during or after the burn. For each test burn, the depth of this thermocouple was recorded as the estimated depth of the 60 °C isotherm. Interpolation was not used to estimate the relative location of the isotherm between two thermocouple locations. For example if the -2.0 cm thermocouple registered a peak temperature 70 °C and the -3.0 cm thermocouple recorded 50 °C , the 60 °C was estimated to be at the -3.0 cm depth. The results of this method which provides a conservative estimate for the 60 °C isotherm are tabulated in Table 3.

3.1 Uncertainty Analysis

There are different components of uncertainty in the temperatures, total heat flux, wind velocity and direction, and marsh sod elevation data reported here. Uncertainties are grouped into two categories according to the method used to estimate them. Type A uncertainties are those which are evaluated by statistical methods, and Type B are those which are evaluated by other means (Taylor and Kuyatt, 1994). Type B analysis of systematic uncertainties involves estimating the upper ($\overline{x}$ + a) and lower ($\overline{x}$ - a) limits for the quantity in question such that the probability that the value would be in the interval ($\overline{x}$ ± a) is essentially 100 percent. After estimating uncertainties by either Type A or B analysis, the uncertainties are combined in quadrature to yield the combined standard uncertainty. Multiplying the combined standard uncertainty by a coverage factor of two results in the expanded uncertainty which corresponds to a 95 percent confidence interval(2σ).

Components of uncertainty are tabulated in Table 4. Some of these components, such as the zero and calibration elements, are derived from instrument specifications. Other components, such as soot deposition or radiation cooling include past experience with thermophoretic deposition on cool surfaces and thermocouples in high temperature fuel rich environments. The combined standard uncertainty for soil temperature and water temperature include a component related to the position of the thermocouple. Each soil thermocouple array was carefully inserted from above the soil line and pulled down through a slot cut in each plant sod. While much care was used in positioning the thermocouple array, the insertion method was more likely to cause a thermocouple to be positioned too high in the plant than too low. A thermocouple that ended up a bit too high would be expected to report higher temperatures than one located at its assigned position. Mixing of the fuel/combustion gases should make position much less of a concern with the air thermocouples. This uncertainty analysis assumed that the thermal conductivity/heat capacity of the soil was relatively uniform and did not include any uncertainty associated with air voids in the soil. Water filled voids were assumed to behave essentially the same as water saturated soil. The total expanded uncertainty was estimated to be -16% to +21 % with the largest components estimated as the position and the repeatability.

Radiation cooling occurs when the hot thermocouple radiates energy to lower temperature environments. The amount of energy which the air thermocouples lost to the cooler water surface depends on the temperature difference between the thermocouple and the water. As the thermocouple experienced higher temperatures, the radiation cooling could have become significant and the thermocouple would have reported lower temperatures than without radiation losses. The total expanded uncertainty for the air temperature data was estimated to be -29 % to +21 % with the largest contributors estimated as the radiation cooling and the repeatability components. Because the water thermocouple were unlikely to lose significant energy via radiation, the total expanded uncertainty for water temperature data was somewhat lower at -16 % to +21%.

The largest components of uncertainty for the total heat flux data were estimated as the repeatability and the effect of soot deposition on the gauge. A layer of soot or small oil drops on the face of the flux gauge, could cause the gauge to under report energy be convected or radiated from the hot combustion products of the fire. The total uncertainty for total heat flux data was estimated to be - 23% to + 22%.

4.0 Discussion

This study exposed a number of *Spartina alterniflora* sods to a spill of refined hydrocarbon, diesel fuel, and then intentionally burned the hydrocarbon until the fuel extinguished itself. The relationship between water level, soil temperature, and plant recovery is not well documented for saltwater marshes or other wetlands environments. In Louisiana marshes alone, over 50 years of marsh burning in marshes has contributed a wealth of experience, but most of the information remains anecdotal. This experience can provide insight into how burning has affected the Louisiana wetlands environment, but before this experience can be extrapolated to other wetland ecosystems, the relationship between fire conditions and plant recovery must be more fully characterized. In order to characterize how the thermal and chemical stresses of and oil spill and it subsequent intentional burning affects the recovery of a salt water marshland ecosystem, this study examine the impact of 1) soil, water, and air temperatures, 2) different water levels, 3), levels of thermal exposure (average and peak total heat fluxes) 4) thermal exposure duration, and 5) pre-burn oil exposure.

4.1 Thermal Stress of *In-Situ* Burning

The thermal stress of fire is a common event in saltwater marshes and other wetland environments. Fires are often ignited by natural phenomenon such as lightning (Lynch 1941, O'Neil 1949) or spontaneous ignition of peat soils (Viosca 1931, Uhler 1944, and Loveless 1959). Fires are also intentionally started to manage marshlands (Stewart 1963, Vogl 1967, and Komarek 1975) to provide better wildlife habitat (Kirby *et al.* 1988 and Schmalzer *et al.* 1991), to make travel easier, and to reduce the number of catastrophic fires (Le Page du Pratz 1758 as cited in Nyman and Cabreck 1995). Marsh fires have been classified into three distinct types, cover, root, and peat burns (Lynch 1941). A cover burn removes the accumulated plant litter and the dense vegetative cover, but does not damage the root system because there is a sufficient water layer above the roots. As the water level drops, the heat from the fire can cause damage to the root systems of the marsh plants. Burns that injure plant roots but do not consume any of the organic peat soil are classified as root burns. And the third type of marsh fire, peat burns, actually burn and consume peat soil as the water levels drop further and/or the intensity of the fire increases.

The three fire types highlight the important role that water (or lack of water) plays in protecting the roots of marsh plants, but it is not clear how much water is sufficient or what soil temperatures result as the water level varies. Lynch (1941) suggested three to five inches of water would afford adequate protection while Mendelssohn, Hester, and Pahl (1996) indicated that soil just needed to be moist or covered with water to shield the roots. How thick the water layer needs to be to protect the roots from thermal damage is not clearly understood.

It is also not well documented what temperatures result from a fire in a marsh. A number of researchers, including Heyward (1938), Bentley and Fenner (1958), Lawrence (1966), and Daubenmire (1968), have reported soil temperatures which occurred during grassland or pine forest fires. While their results provide insight for dry soils, marsh soils are much wetter and it is not clear whether additional water will provide better heat conduction into the soil or whether the dry soil will provide better insulation. Heyward (1938) stated that as moisture content increases, heat conduction through a soil increases up to a point, then remains constant. Lethal temperatures for most plants, excluding algaes and mosses, appear to be in the range of 60 °C to 65 °C (Byram 1948, Ahlgren 1974, and Levitt 1980).

This study monitored soil temperatures as a function of water level, soil depth, and burn duration. Peak soil temperatures, including the average and range of the values, are tabulated in Table 3. At the -10 cm sod elevation, the temperatures recorded at the soil surface did not exceed 50 °C. This demonstrates that 10 cm of water over the soil would prevent root burn. For marsh sods positioned at the -2 cm, average peak temperatures for the soil surface thermocouples was slightly less than 60 °C, but two of the sods did see temperatures of 68 °C and 70 °C. The surface

Table 1. Peak Temperatures and Estimated Depth of 60 °C Isotherm

	Plant Elevation							
	Pre-Burn Oiled				Un-Oiled			
	-10cm	-2cm	0cm	10 cm	-10cm	-2cm	0cm	10cm
400 s *In-Situ* Burn Exposure								
Exp. 5-1 Peak Temp. °C T/C < 60 °C	TS32	TS33					TS12	TS28
Exp. 5-5 Peak Temp. T/C < 60 °C	TS23 34 °C 0 cm	TS29 68 °C -0.5cm	TS38 70 °C 0 cm	TS11 350 °C - 3 cm				
Exp. 5-3 Peak Temp. T/C < 60 °C	TS03 35 °C 0 cm	TS30 56 °C 0 cm	TS47 64 °C -0.5cm	TS26 400 °C -2 cm				
Exp. 5-2 Peak Temp. T/C < 60 °C			TS04 64 °C -0.5cm	TS45 380 °C -2 cm	TS17 31 °C 0 cm	TS50 47 °C 0 cm		
Exp. 5-4 Peak Temp. T/C < 60 °C					TS01 36 °C 0 cm	TS15 58 °C 0 cm	TS37 120°C -2 cm	TS13 300 °C -5 cm
1400 s *In-Situ* Burn Exposure								
Exp. 20-2 Peak Temp. T/C < 60 °C	TS49 40 °C 0 cm	TS09 480°C -5 cm	TS20 58 °C 0 cm	TS07 150 °C -5.0 cm				
Exp. 20-1 Peak Temp. T/C < 60 °C					TS 14 50 °C 0 cm	TS34 70 °C -0.5 cm	TS06 100°C -2 cm	TS19 600 °C -5 cm
Exp. 20-5 Peak Temp. T/C < 60 °C					TS35 42 °C 0 cm	TS24 56 °C 0 cm	TS48 90 °C -3 cm	TS44 580 °C -7 cm
Exp. 20-3 Peak Temp. T/C < 60 °C	TS46 42 °C 0 cm	TS02 51 °C 0 cm					TS16 58 °C 0 cm	TS25 800 °C -7 cm
Exp. 20-4 Peak Temp. T/C < 60 °C			TS22 82 °C -2 cm	TS39 800 °C -5 cm	TS40 35 °C 0 cm	TS42 58 °C 0 cm		

Notes:
1) Burn 5-1 data were lost due to data acquisition memory difficulties.
2) TS xx is plant identification number.
3) Peak temperature is value reported by thermocouple located at soil surface (0 cm).
4) T/C < 60 °C is depth of thermocouple reporting temperature which did not exceed 60 °C .
5) Uncertainties discussed in Section 3.1

Table 2. Burn Durations, Average Total Heat Flux, and Wind Data

Burn ID	Burn Duration s	Total Heat Flux East Diving Bell Average kW/m^2	Std. Dev.	Total Heat Flux West Diving Bell Average kW/m^2	Std. Dev.	Wind Average Velocity m/s	Wind Average Direction Degrees
5-1	421					2.1	225
5-5	415	108	± 12	102	± 28	0.9	138
5-3	415	106	± 18	122	± 21	0.9	120
5-2	3.75	96	± 17	115	± 20	1.4	139
5-4	430	109	± 20	124	± 14	2.1	88
20-2	1370	130	± 14	95	± 13	2.6	265
20-1	1365	119	± 12	98	± 11	2.7	237
20-5	1395	110	± 12	102	± 19	2.9	287
20-3	1460	102	± 15	102	± 19	1.2	102
20-4	1390	100	± 13	124	± 19	1.3	77

Notes:
1) North = 0 degrees South = 180 degrees
Total Heat Flux Gauge (X) = 70 degrees
Total Heat Flux Gauge (Y) = 265 degrees
2) Wind direction is defined as direction wind is blowing from, so a 77 degrees wind is blowing from 77 degrees.

Table 3. Average Peak Soil Temperatures and Estimated Depth of 60 °C .

Sod Elevation	Average Burn Duration s	Peak Soil Temperature Average * °C	Peak Soil Temperature Range °C	Estimated 60 °C Isotherm** Average Depth cm	Estimated 60 °C Isotherm** Range Of Depths cm
-10 cm	400 1400	34 43	31 to 36 35 to 50	0 0	0 0
-2 cm	400 1400	57 59	47 to 68 51 to 70	-0.13 -0.13	-0.5 to 0 -0.5 to 0
0 cm	400 1400	66 72	64 to 70 58 to 90	-0.75 -1.4	-2 to 0 -3 to 0
+10 cm	400 1400	360 700	300 to 400 580 to 800	-3.0 -6.3	-5 to -2 -7 to -5

Notes:
* Average Peak Soil Temperature - peak temperature recorded at soil surface thermocouple. Values from all plant sods at each plant elevation averaged.
** 60 °C Isotherm - depth in soil where temperature which did not exceed 60 °C during or after (90 minutes) burn exposure.

Table 4. Uncertainty in Experimental Data.

	Component Standard Uncertainty	Combined Standard Uncertainty	Total Expanded Uncertainty
Soil Temperature			
Calibration	± 1 %		
Position	- 2 % to + 7 %	- 8 % to + 10 %	- 16 % to + 21 %
Repeatability	± 7 %		
Random	± 3 %		
Total Heat Flux			
Calibration	± 2 %		
Zero	-0 % to + 2 %	- 12 % to + 11 %	- 23 % to + 22 %
Soot Deposition	- 5 % to + 0 %		
Repeatability	± 10 %		
Random	± 3 %		
Air Temperature			
Calibration	± 1 %		
Radiation Cooling	- 10 % to + 0 %	- 14 % to + 10 %	- 29 % to + 21 %
Repeatability	± 10 %		
Random	± 3 %		
Water Temperature			
Calibration	± 1 %		
Position	- 2 % to + 7 %	- 8 % to + 10 %	- 16 % to + 21 %
Repeatability	± 5 %		
Random	± 6 %		
Sod Elevation			
Repeatability	± 2 %	± 3 %	± 6 %
Random	± 2 %		
Wind			
Velocity			
Repeatability	± 5 %	± 5 %	± 11 %
Random	± 2 %		
Direction			
Repeatability	± 3 %	± 4 %	± 7 %
Random	± 2 %		
Note: Random and repeatability evaluated as Type A, other components as Type B.			

thermocouple (0 cm) in marsh sod TS09 did report a much higher temperature of 480 °C, however pre-burn sod observations noted that the soil/root mass was densely packed roots and the post-burn observations noted that the sod had opened up to expose the top two thermocouples. Results from TS09 were not included in the peak temperature averages or estimated depth of 60 °C isotherm. The duration of the burn, whether it was 400 s or 1400 s, did not appear to make much difference in soil surface temperatures for the sods positioned either -10 cm or -2 cm.

For sods that were positioned so that the soil line was at the surface of the water, 0 cm, peak temperatures at the surface averaged around 80 °C which is higher than the 60 °C to 65 °C range that appear to be lethal to most plants. However, it is important to note that the 80 °C average value was at the surface and below the surface, soil temperatures decreased. The estimated depth of the 60 °C isotherm was from 0 cm to 3 cm below the soil surface. Since the root system appeared to extend down 15 cm or 20 cm below the soil line, it is not clear that if the upper 3 cm exceeded 60 °C that this would cause the plants to die. The plant recovery data will provide insight into whether soil temperatures of 60 °C at -3 cm are sufficient to kill the plant. Pre-burn sod observations noted that the top thermocouples for TS37 and TS06 were exposed probably because the soil had subsided after the thermocouple array had been inserted. This exposure resulted in both TS37 and TS06 recording significantly higher temperatures that the other sods at the same elevation. These temperature values were not included in calculated average peak temperatures in Table 3.

Marsh sods which were positioned at +10 cm recorded the highest average peak soil temperatures, 360 °C and 700 °C , for the 400 s and 1400 s, respectively. The difference in average peak temperatures is a reflection of the difference in exposure times. This difference between the sods exposed to 400 s and 1400 s of fire was not observed in the -10 cm, -2cm, or 0 cm elevations. The estimated depth for the 60 °C was -3 cm for the shorter burn duration and -6 cm for the longer exposure. Again since the root system appeared to extend down 15 cm or 20 cm below the soil line, it is not clear that if the upper 3 cm to 6 cm exceeded 60 °C that this would cause the plants to die. The plant recovery data will provide insight into whether soil temperatures of 60 °C at -6 cm are sufficient to kill the plant. Marsh sod TS07 recorded unusually low temperatures and it is likely that the drain at the bottom of the container was not open. The drain should have allowed the water level in the container to equilibriate with the water level in the tank. If this drain was clogged, then the container would have remained filled with water and the thermocouples would have recorded low values. The temperature data from TS07 was not included in the computation of average peak temperature values.

The different burn exposures of either 400 s or 1400 s did not appear to cause significantly different average peak temperatures at the soil surface in the -10 cm, -2 cm, or 0 cm elevations. The average peak soil surface temperatures were remarkably higher in the 1400 s exposure as compared to the 400 s exposure. The short and long burn exposures were designed to simulate the different exposures that a marsh ecosystem may experience during an *in-situ* burn. For sections of the marsh with relatively thin layer of spilled oil, burn exposure is likely to be shorter than marsh areas where the spilled oil has pooled into deeper layers. For the 400 s exposure, soil temperatures at the surface were not similar to the air temperatures recorded at +10 cm. After 1400 s of exposure, the soil surface thermocouples were within 200 °C of the air temperatures monitored at +10 cm. Qualitatively, it appeared as though the top of the soil was beginning to approach equilibrium with the air just above the soil. It is important to note that this only occurred in the +10 cm plant sods which were above the water line. As shown in Figure 14, the temperature of the 0 cm, -0.5 cm, 1 cm, and 2 cm thermocouples increase quickly to 100 °C, then remain steady at 100 °C for a period of time and then begin increasing again. This steady behavior at 100 °C resulted because the water in the soil begin to boil and then evaporate. The water acts to limit the soil temperature at that depth until the water has evaporated. This behavior was present in the 400 s exposure, but not as pronounced as in the 1400 s exposure. While it is not clear what the average exposure to fire would be for a specific fire in a wetlands, the 400 s and 1400 s provide two different exposures for comparison.

Pre-burn oiling of the marsh sods did not appear to have any significant impact on the soil temperatures. It was not expected that the pre-oiling would affect the thermal conductivity of the soil. The pre-burn oiling was designed to provide a chemical stress, not a thermal stress, to the marsh sods.

Total heat flux was monitored by two vertically facing total heat flux gauges located 10 cm above the water surface and the combined average total heat flux for the East and West gauges were 98 kW/m^2 and 109 kW/m^2, respectively (Table 2). These values are similar to the average values reported for burning diesel fuel on water (Walton *et al.* 1999). Some the differences between the East and West flux values do appear to correlate with the wind direction. During Test 20-2 the wind was blowing from the direction of 265 degrees and would have caused the fire plume to lean or bend over towards the East total heat flux gauge. The East gauge recorded an average of 130 kW/m^2 while the West gauge reported an average of 95 kW/m^2. In a similar fashion, during Test 20-4, the wind was blowing from 77 degrees and caused the plume to bend towards the West gauge. This resulting in an average total heat flux of 124 kW/m^2 and 100 kW/m^2 for the West and East gauges, respectively. The total energy which a plant may experience or be exposed to during an *in-situ* burn can be estimated from this total heat flux data.

4.1 Chemical Stress of Oil Toxicity

The chemical stress imposed by spilled oil includes the toxicity of hydrocarbon spilled and the duration of the exposure. If the oil is not removed from the wetlands, the stress on the marsh vegetation can range from short-term depressions of photosynthesis to near total mortality (Baker 1970, Alexander *et al.* 1985, and Mitsch and Gosselink 1993, and Pezeshki et al. 1995). Lower molecular weight or lighter hydrocarbons tend to be more acutely toxic than higher molecular weight or heavier compounds (Baker 1970). Crude oil or refined products which contain significant fractions of lighter hydrocarbons such as gasoline or diesel fuel tend to be more toxic than those which are predominantly heavier hydrocarbons such as tars, asphaltenes, and waxes.

The duration of exposure to spilled hydrocarbons also plays an important role in the recovery or lack of recovery of the exposed vegetation. If an oil spill is undiscovered for weeks and clean up is delayed, then chances for recovery and regrowth are greatly diminished. If the spill is detected quickly and the oil cleaned up thoroughly and rapidly, the prospects for recovery of the plants is improved. Many factors including wind, temperature, water level, tides, and soil types affect the extent to which spilled oil will penetrate a salt marsh. All of the above research on oil toxicity and exposure provide much insight into how spilled hydrocarbons, both crude and refined, may impact a salt marsh while reinforcing the need to insure that the oil is removed from the wetlands environment.

The experimental design matrix for this series of burns included exposing forty of the plants to the chemical stress of pre-burn oiling with diesel fuel. Diesel fuel was selected to be the pre-oiling agent because it is a commonly refined hydrocarbon product and each burn was to be fueled using diesel. Previous work at LSU also involved exposing different plant species to diesel fuel. The pre-burn oiling at the rate of 1 liter/m^2 was applied 24 hours before each burn and was designed to stress the affected plant sods, but not kill the plants. Diesel fuel is typically very toxic to plants since it usually contains a significant fraction of lower molecular weight hydrocarbons.

Originally, the experimental design limited the amount of chemical stress to just the pre-burn oiling with diesel fuel. However, access holes were drilled in the sides of the containers holding the -2 cm and 0 cm plant sods in order to allow the water level in the container to equilibrate with the water level in the burn tank. Just before each burn, the diesel fuel was floated on top of the water and the diesel fuel also entered through these access holes and surrounded the plant stems. Any sections of soil which extended above the water line also came into contact with the diesel fuel. The diesel fuel would have remained in contact with the plants and soil throughout the burn exposure. The contact exposure would have been limited to about 600 s and 1600 s for the 400 s and 1400 s burns, respectively. Once the diesel fuel extinguished itself, a water stream was used to herd the floating oil residue away from the plant sods. It is not clear what impact, if any, this diesel fuel may have had on the subsequent recovery of the plants. It may be difficult to separate the exposure to "pre-burn" and "intra-burn" diesel fuel. Soil samples were collected from control plants, pre-burn oiled plants, and post-burn sods. The oil chemistry analyses which was conducted on soil samples should demonstrate how deep the diesel fuel penetrated the soil of the plant sods. The subsequent recovery or lack of recovery of the plant sods will provide additional understanding about the impact of the chemical stress of oil toxicity.

In-situ burning of crude or refined hydrocarbons can be used by oil spill remediation teams in order to minimize the impact of spilled oil within a wetland environment. Intentionally burning the oil in place can prevent the spilled oil from spreading to additional areas and can help remove much of the spilled hydrocarbons from the affected wetlands. However, *in-situ* burning of the oil will impose an additional thermal stress on the same plants which have already been exposed to the chemical stress of the oil toxicity. If the oil toxicity has already killed the plants within the spill boundary, then exposing the plants to the thermal stress of *in-situ* burning is a moot point from the perspective of plant survivability. Even if all or most of the plants have succumbed to the chemical stress, *in-situ* burning may still play an important role in removing the oil from the marsh. If the plants have not succumbed to the chemical stress, *in-situ* burning may offer a less intrusive and less stressful technique than mechanical oil recovery to remove the oil from the wetlands.

5. Conclusions

Eighty sods of *Spartina alterniflora* were exposed to the combined chemical and thermal insult which marsh plants might encounter during an *in-situ* oil spill burn in a series of full-scale diesel fuel burns. The thermal stress of an *in-situ* burn was characterized by monitoring soil, water and air temperatures as well as total heat flux. The soil temperature data demonstrates that 10 cm of water over the soil line is definitely sufficient to prevent soil temperatures from reaching the 60 °C range where permanent damage will occur in most plants. A layer of water, just 2 cm deep appeared to provide enough thermal protection to limit peak temperatures at the soil surface to around 70 °C. Only when the soil line is at or above the water line did the soil temperatures consistently exceed the 60 °C range where plant survivability data suggest permanent damage begins to occur. Plant sods which were positioned 10 cm above the water level appeared to suffer permanent damage. The total heat flux data confirms that these burns were large enough to simulate the heat flux and temperature of full-scale fires.

The thermal stress imposed by fire is only part of the stress imposed by an *in-situ* burn. The chemical stress of an oil spill in a marsh environment was simulated by pre-oiling 40 of the plant sods. As the plants are monitored through a growth cycle (April 2000), the resulting recovery and regrowth data will better characterize the impact of the chemical stress of an oil spill which was intentionally burned.

For this set of diesel fuel burns the soil temperature data indicates that a 2 cm layer of water appears to provide sufficient protection from permanent damage, however, the soil temperature is but one of many factors which may influence the impact of an *in-situ* burn on the wetlands ecosystem. Along with the interaction between the thermal and chemical stresses, the impact of other factors including plant species, growth cycle, soil type, and fuel chemistry must also be more fully characterized and understood if we are to consider, on a routine basis, *in-situ* burning for the remediation of oil contaminated wetlands.

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