In-Situ Oil Burning in the Marshland Environment - Soil Temperatures Resulting from Crude Oil and Diesel Fuel Burns

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A series of crude oil and diesel fuel burns was conducted to examine the impact of intentional burning of oil which was spilled in a wetlands environment. Oil spilled in sensitive marsh environments pose unique challenges associated with cleanup because mechanical recovery in wetlands may cause more damage to the marsh than the oil itself. *In-situ* burning of oiled marshes may provide a less damaging alternative than traditional mechanical recovery, but many factors, including plant species, fuel type and load, water level, soil type, burn duration, may influence how well a wetlands recover from an *in-situ* oil burn.

Five diesel fuel and six crude oil burns were conducted in a 6 m diameter test tank to monitor the soil temperatures at three different soil/water elevations for 700 s burn exposure. One hundred eighty-four plant sods, *Spartina Alterniflora*, *Spartina Patens*, and *Sagittaria Lancifolia*, each 30 cm in diameter and 30 cm of soil depth, were harvested from marshlands in southern Louisiana. Fifty-seven plant specimens were instrumented with thermocouples inserted into the soil to monitor soil temperature. Thermocouples were inserted at (0, 0.5, 1, 2, 3, 5, 7, and 10) cm below the soil line. Water and air temperature as well as total heat flux 10 cm above the water surface were also recorded. For each of the eleven burns, between ten and sixteen specimens, about one-third instrumented, were positioned at +2 cm, -2 cm and -10 cm relative to the water level. Diesel fuel or crude oil was added to surface of water, ignited, and allowed to burn for a period of 700 s. As a function of plant elevation and soil depth, the soil temperatures were recorded. For plants positioned 2 cm above the water level, peak soil temperatures ranged from 90 °C to 100 °C for each of the three plant species. Plants specimens which were located 10 cm below water level did not exceed 40 °C during the burn exposure of 700 s or the 4700 s post-burn temperature monitoring period. The diesel fuel and the crude oil burns produced similar soil temperature profiles at each of the three plant sod elevations.

1.0 Introduction

Oil spills of crude or refined hydrocarbons in wetland or saltwater marsh

Arctic and Marine Oilspill Program (AMOP) Technical Seminar, 24th. Proceedings. June 12-14, 2001, Edmonton, Canada, Environment Canada, Ottawa, Ontario, 729-753 pp, 2001.

ecosystems provide unique challenges for oil spill clean-up teams. Typically an oil spill response team may allow the oil to remain in the marshland environment or may attempt to remove the oil using mechanical recovery methods. If the oil is not removed from the marshland, the toxic properties of most petroleum hydrocarbons (Baker, 1970) are likely to kill most of the plants within the initial spill boundary. Tidal and/or wind action can spread the oil to additional marsh areas which may include more environmentally sensitive wetlands such as breeding habitats. The oil toxicity and likelihood of the oil spreading usually causes the response team to employ mechanical remediation which often includes the use of heavy equipment such as backhoes, loaders, and dump 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 heavy equipment can do more damage to these highly fragile marshlands than the oil toxicity itself. Obviously, a remediation technique that removes spilled oil from the wetlands while causing less damage than mechanical reclamation would be extremely valuable option for oil spill cleanup teams. A major goal of the oil spill response community, including the Minerals Management Service and private oil spill response companies, has been to develop remediation methodologies that are less damaging to the saltwater marshes while still cleaning up the oil spill.

In-situ burning or intentional burning of spilled oil 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 saltwater marsh and preventing the spread of the oil to other environmentally sensitive areas. However, intentional burning of spilled hydrocarbons imposes a fire or thermal stress on the wetland plants which have already been exposed to the chemical toxicity of the oil. For example, if the soil temperatures exceed 60 °C, most plants would suffer permanent damage (Byram 1948, Levitt 1980, and Ahlgren1974), but water levels in the marsh could provide adequate protection against the thermal stress of an *in-situ* burn.

A set of experimental burns by Bryner *et al.* (2000) and Lin *et al.* (2001) exposed ninety *S. alterniflora* plant mesocosms to burning diesel fuel and helped characterize the thermal and chemical stresses which occur during an *in-situ* burn. During burn exposures of either 400 s or 1400 s, instrumented plant sods were positioned at different elevations, +10 cm, 0 cm, -2 cm, and -10 cm. A +10 cm plant elevation positioned the soil line 10 cm above the water surface while a -10 cm location placed the soil line 10 cm below the water surface. Plants positioned at +10 cm recorded average peak temperatures ranging from 360 °C (400 s) to 700 °C (1400 s) at the surface of the soil. The average depth of the 60 °C isotherm in the soil ranged from 3 cm (400 s) to 6 cm (1400 s). Thermal stress almost completely inhibited the post-burn recovery of *S. alterniflora* mesocosms positioned at +10cm. On the other hand, plants with soil lines positioned at -10 cm appeared to be insulated by the water layer from the thermal stress of *in-situ* burning and recovered quite well. The lethal temperature for *S. alterniflora* appeared to be 60 °C at 2 cm below the soil surface, although it may vary with plant species. Other mesocosms located at either 0 cm or -2 cm did not recover as well as the -10 cm plants and the poor recovery was most likely due to hydrocarbon stress induced by diesel fuel entry into the soil. The high concentration of diesel fuel in the soil at these water levels most likely caused greater plant stress than the thermal stress. Although *in-situ* burning did not appear to remediate oil that had penetrated into the soil, it did effectively remove floating oil from the water surface, thus preventing it from potentially contaminating adjacent habitats and penetrating the soil when the water recedes.

The overall goal of this study is to build upon the work of Bryner *et al.* (2000) and Lin *et al.* (2001) and continue 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 184 specimens of *Spartina alterniflora*, *Spartina Patens*, and *Sagittaria Lancifolia* plants to burning diesel fuel and crude oil in order to collect data on how the regrowth and recovery of marsh plants are effected by 1) soil, water, and air temperatures, 2) different soil line elevations, 3) levels of thermal exposure from different fuels, 4) response of different plant species, and 5) pre-burn oil exposure. This report will focus on soil, air, and water temperatures, as well as total heat fluxes that resulted when three plant species were exposed to full-scale *in situ* burns that were created by burning diesel fuel and crude oil. 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 *in-situ* burning requires that the plants be observed through at least one growing season. The regrowth and recovery of the plants will be more fully described in a separate report.

2.0 Experimental Apparatus and Procedure

One hundred and eighty-four specimens of marsh plants 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 eleven experimental burns. For each of the burns, between 10 and 16 mesocosms, five instrumented and the others un-instrumented, were positioned at + 2 cm, -2 cm and -10 cm relative to the water level (Table 1). These different water level/ soil elevations were designed to mimic the natural variation in water level /soil heights in a salt marsh. Sixty-four of the specimens were pre-oiled with diesel fuel or crude oil to simulate exposure to spilled oil before spill response team initiates clean-up. Fifty-seven of the plant specimens were instrumented with thermocouples 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. A more detailed description of the experimental apparatus and procedure, including the round tank burn facility, ignition and fueling procedure, plant specimen containers, soil thermocouple insertion, soil, water, and air temperature instrumentation, and post burn exposure plant monitoring, was included in Bryner *et al.* (2000).

2.1 *In-Situ* Burn Exposure

In-situ burning of an oil spill in wetlands was simulated by burning a 1.8 cm thick layer of fuel which was floating on water that was 71 cm deep. In five tests, 10-1 through 10-5 (Table 1), diesel fuel was burned while in six tests, 10-7 through 10-12, southern Louisiana crude oil was used as fuel. For each of the 700 s burns, sufficient fuel was added for 300 s of burn and the fuel flow was turned off. The fuel

Table 1. Plant Sod ID Numbers, Elevations, Instrumentation, and Oiled / Unoiled Matrix

Test ID	UnOiled + 2 cm	UnOiled - 2 cm	UnOiled -10 cm	Oiled + 2 cm	Oiled - 2 cm	Oiled -10 cm
10-1	A235 P51**	P273	A151 P114	A18**	A15* P53*	A40* P113
10-2	A25** P272	A23*	A244	P54**	A136 P57*	P10*
10-3	A243 P61**	A158 P59*	A28* P4*	P5**	A240	A16 P205
10-4	A29** P115	A1* P220	P110	A227 P3**	A31* P109	A32*
10-5		A128 P65*	A27* P60*	A26** P134	A17* P124	A167 P58*
10-7	A13**	A21* P204 L94	A241 L77	P44** L100	P35*	A233 P42* L104
10-8	A242 P56** L107	A147 P64* L108	P138	A20**	A19* P111 L105	A33* L96
10-9	A168	A22* P120 L87	P62* L80	A153	P63* L103	A14* P12* L102
10-10	P232 L82	A38* P208	A11* P9* L106	A8** P55** L91	A236 P116 L90	A237 P135
10-11	P7** L81	P69 L39*	A30* P218	P207 L41*	A24 P203	A145 P215 L73
10-12	P132 L48**	P2*	P70 L37*	A142 P216 L74	A34* P6* L36	P209

Control Sods	
Control (no burn/no oil/no cut)	A169 A238 A146 A229 P206 P219 P228 P201 L84 L75 L95 L101
Diesel Oiled (no burn / no cut)	A129 A239 A139 A152 P274 P217 P68 P231 L49 L76 L89 L85
Crude Oiled (no burn / no cut)	A131 A155 A224 A170 P202 P66 P133 P119 L83 L86
Cut Control (no burn / no oil)	A148 A126 A144 A156 P117 P211 P230 P67
Cut / Diesel Oiled (no burn)	A137 A223 A154 A143 P222 P112 P221 P122
Cut / Crude Oiled (no burn)	A141 A234 A130 A225 P72 P71 P210 P121

* Instrumented with an array of 4 thermocouples
** Instrumented with an array of 8 thermocouples
A - *Spartina Alterniflora* P - *Spartina Patens* L - *Sagittaria Lancifolia*

was ignited and the fuel flow was restarted at a rate of approximately 120 l/min which was designed to maintain the fuel layer at a constant 1.8 cm thickness. After approximately 400 s, the 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 120 l/min, results in an estimated heat release rate of about 50 MW for each of the diesel fires. While the target burn durations were 600 s, actual burn exposures ranged from 600 s to 810 s. The plant specimens were then returned to LSU greenhouses to monitor regrowth and recovery of the plants.

2.2 Plant Elevations in the Round Tank Burn Facility

This burn series was conducted in the 6 m diameter round tank facility at the Fire and Emergency Training Institute (FETI) at Louisiana State University just outside of Baton Rouge, Louisiana. Within this tank, sixteen plant support stands were positioned in 1.5 m and 3.0 m diameter circles. Each stand supported a potted plant specimens at -10 cm , -2 cm, or +2 cm relative to the surface of the water. As described in Table 1, each experimental burn exposed plants of different species, at different elevations, oiled and unoiled, as well as instrumented and un-instrumented.

Within the burn tank, each plant was placed on its assigned stand, adjusted to the proper elevation, and then leveled. A -10 cm plant was located so the average soil level was 10 cm below the water surface. The plants positioned at -2 cm elevations were not positioned using average soil levels, but according to peak soil heights. The work of Lin *et al.* (2001) reported that many of the sods which had been positioned at 0 cm and -2 cm had unintentionally been contaminated with diesel fuel when the diesel fuel was floated on the water prior to and during the in situ burn. If the soil within a sod did not have a flat profile, a peak of soil could extend above the surface of the water and as fuel was added to the burn tank, this soil peak appeared to absorb or wick oil into the soil. This "rogue" oil introduced a chemical stress that was sufficient to reduce significantly the regrowth of the plants. To prevent contamination via "rogue" oil in this study, the plants at the -2 cm elevations were positioned using peak soil line elevations, rather than the average soil levels. A -2 cm plant was elevated in a manner that 2 cm of water was over the highest part of the soil in the container. Plants placed at +2 cm still positioned using average soil levels, but in order to prevent the exposed soil from absorbing fuel, a 10 cm tall steel collar was installed in each container. For plants which were to be positioned at the -2 cm positions, four access holes, each 1 cm in diameter, were drilled at the water line. These access holes were designed to allow the water in the plant specimen to equilibriate with the water level in the tank. For each +2 cm plant where a collar had been installed, the water level was manually adjusted to match the tank water level just before the fuel was added to the tank.

2.3 Plant Specimens

One hundred eighty four specimens, including 71 *S. alterniflora*, 79 *S. patens*, and 34 *S. lancifolia* sods, were collected from three separate locations in southeast Louisiana. After collecting a 30 cm diameter and 30 cm deep plant sod section, each specimen was placed into a 20 liter (five gallon) container and transported to Louisiana State University (LSU) greenhouses in Baton Rouge. Each plant specimen was assigned a unique number. Plant specimens were randomly assigned to different elevations, specific burns, and whether or not to be pre-oiled. For example as indicated in Table 1, specimen A18 was instrumented with an array of 8 thermocouples was pre-oiled, positioned at +2 cm and exposed during Test 10-1. Twenty-four control sods were included for burn / no burn, oil / no oil, and cut / no cut for both *S. alterniflora* and *S. patens* species (Table 1). Only ten *S. lancifolia* sods were included as burn / no burn and oil / no oil control sods. The burn / no burn and oil / no oil controls were used in assessing the impact of thermal and chemical stress, respectively. The cut / no cut controls were included to examine the effect of a sod's foliage being burned off during exposure to an *in-situ* burn. The foliage of each "cut" control was manually trimmed so that it's regrowth and recovery could be compared to plant sods "trimmed" by exposure to an *in-situ* burn.

In order to simulate the exposure to spilled oil before the remediation team arrives, 64 sods were oiled 24 hours before being exposed to *in-situ* burning. Pre-oiling was implemented at the rate of 1 L/m^2 which resulted in approximately 70 mL of diesel fuel or crude oil being added to a 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 Instrumentation

Fifty-seven of the plant specimens were instrumented with thermocouple arrays in order to track the vertical temperature gradients within the soil. Thirty-eight specimens were instrumented with the arrays consisting of four Chromel- Alumel thermocouples while the remaining specimens included arrays of eight thermocouples. An eight thermo-couple array consisted of thermocouples positioned at (0, - 0.5, -1, - 2, - 3, - 5, - 7, and - 10) cm below the soil line while a four thermocouple array featured thermocouples at (0, - 0.5, - 2, and - 5)cm.

Two additional arrays of seven thermocouples in the tank monitored the water and air temperatures during each burn. Thermocouples monitored the temperature of air or combustion products at +10 cm and +20 cm above the 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 water/air temperature thermocouple arrays. 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.

2.5 Post Burn Monitoring

Once the plant specimens 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. The effect of water level and fuel load on wetland vegetation recovery will be assessed by measuring plant growth responses including plant biomass, stem height, and density as well as leaf

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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.

photosynthesis, the latter a sensitive indicator of plant response to stress. Plant regrowth, which will be used to assess vegetation recovery, will be assessed by measuring plant height and density as well as live and dead above- and below ground biomass at the termination of the experiment. Oil chemistry will characterize the oil before and after each burn to estimate burn fractions and homogeneity of the plot exposures to the oil. Chemical 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.

The monitoring protocol, oil chemistry, and chemical analyses is described in detail in Lin *et al.* (2001). Since the plants were exposed to *in-situ* burns during the last two weeks of August 2000, it will be necessary to monitor the plants through at least one growth cycle which should occur before May 2001. The results and conclusions of the plant regrowth and recovery will appear in a separate report.

3.0 Results

Soil, water, and air temperatures and total heat flux were graphed versus time for each of eleven burns. Plant specimens will be identified by the elevation of the soil line relative to the water level in the tank or -10 cm, -2 cm, or +2 cm plants. The soil line of a +2 cm plant specimen was 2 cm above 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 specimen will be identified by the position of the thermocouple relative to the soil line of the plant specimen 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 specimen 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 appears and ignition always occurs at 600 s.

For *S. alterniflora*, *S. patens*, and *S. lancifolia*, soil temperature versus time for +2 cm elevations from crude oil burns are plotted in Figures 1, 2, and 3, respectively. Each of these three plant specimens was pre-oiled. The crude oil fuel was ignited at 600 s and burned for approximately 700 s. As these figures demonstrate, peak soil temperatures *S. alterniflora*, *S. patens*, and *S. lancifolia* plants were 94 °C, 98 °C, and 94 °C, respectively. The burn duration, 700 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 as the fuel extinguished itself.

For each of the three species, soil temperature versus time for -2 cm elevations from crude oil burns are plotted in Figures 4, 5, and 6, respectively. The *S. alterniflora* and *S. patens* sods were pre-oiled while the *S. lancifolia* was not pre-oiled. The crude oil fuel was ignited at 600 s and burned for approximately 700 s. As these figures demonstrate, peak soil temperatures for *S. alterniflora*, *S. patens*, and *S. lancifolia* plants were 46 °C, 44 °C, and 40 °C, respectively. While the upper thermocouples, 0 cm and -0.5 cm began to increase in temperature as the crude oil fire extinguished itself (around 1300 s), the lower thermocouples at -2 cm and -5 cm, were still increasing slightly nearly 90 minutes after the fuel extinguished itself.

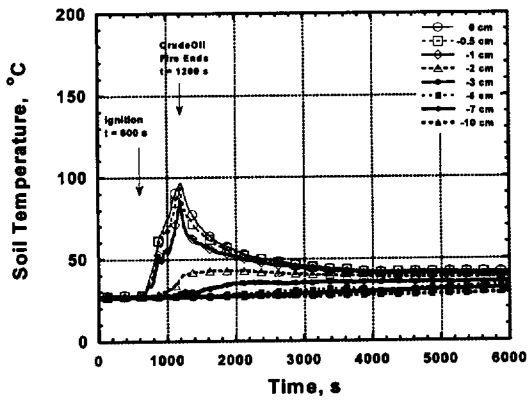

Figure 1. Temperature vs Time for a 700 s *In-Situ* Crude Oil Burn Exposure with *S. Alterniflora* Sod at +2 cm Elevation.

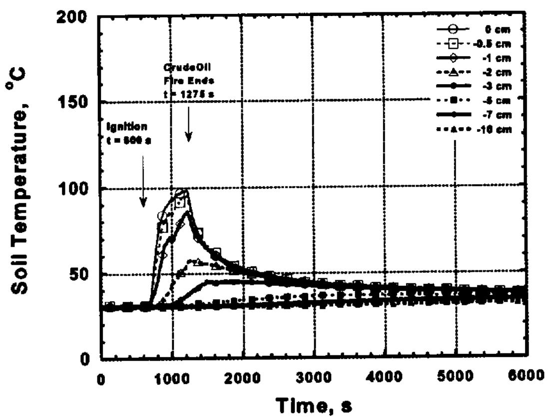

Figure 2. Temperature vs Time for a 700 s *In-Situ* Crude Oil Burn Exposure with *S. Patens* Sod at +2 cm Elevation.

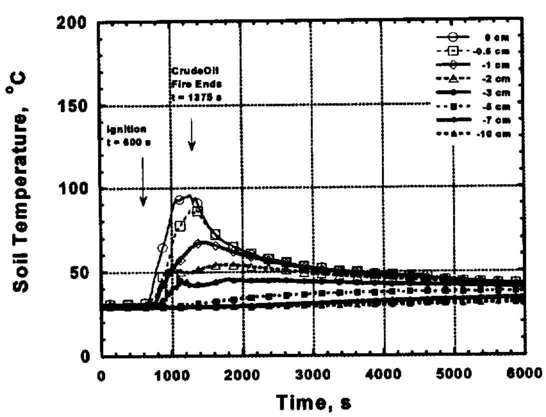

Figure 3. Temperature vs Time for a 700 s *In-Situ* Crude Oil Burn Exposure with *S. Lancifolia* Sod at +2 cm Elevation.

For *S. alterniflora*, *S. patens*, and *S. lancifolia*, soil temperature versus time for -10 cm elevations from crude oil burns are plotted in Figures 7, 8, and 9, respectively. The *S. alterniflora* and *S. patens* sods were pre-oiled while the *S. lancifolia* was not pre-oiled. The crude oil fuel was ignited at 600 s and burned for approximately 700 s. As these figures demonstrate, peak soil temperatures *S. alterniflora*, *S. patens*, and *S. lancifolia* plants were 34 °C, 33 °C, and 32 °C, respectively. The soil temperature did not typically begin to increase until at least 700 s after the crude oil extinguished itself. All thermocouples were still reporting slight increases in soil temperature nearly 90 minutes after the fuel extinguished itself.

Air and water temperatures are plotted in Figures 10 and 11 for crude oil burns and Figures 12 and 13 for diesel fuel burns. Peak air temperatures of about of about 900 °C and 850 °C for the diesel fuel and crude oil, respectively. Water temperatures for both the diesel fuel and crude oil appeared similar in the range of 100 °C to 230 °C. 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 heat flux gauges for diesel fuel and crude oil burns are plotted in Figures 14 and 15, respectively. Similar to the work of Bryner *et al.* (2000), the diesel fuel burns show peak values of energy flux exceeded 150 kW/m^2 with an average value of 100 kW/m^2 (5 burns x 2 gauges). The crude oil burns demonstrate significantly lower peak value of 110 kW/m^2 with a lower average value of 80 kW/m^2 (6 burns x 2 gauges). During the crude oil burns, an oily soot "crust" formed on the water cooled heat flux detector. The presence of this crust may have absorbed some of the radiation before it was recorded by the heat flux detector.

Peak soil temperatures for each of three species are tabulated in Table 2, 3, and 4 for diesel fuel and crude oil burn experiments. Average total heat flux values, burn durations, and wind data for each experiment are compiled in Table 5. 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 6.

3.1 Uncertainty Analysis

There are different components of uncertainty in the temperatures, total heat flux, wind velocity and direction, and plant 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

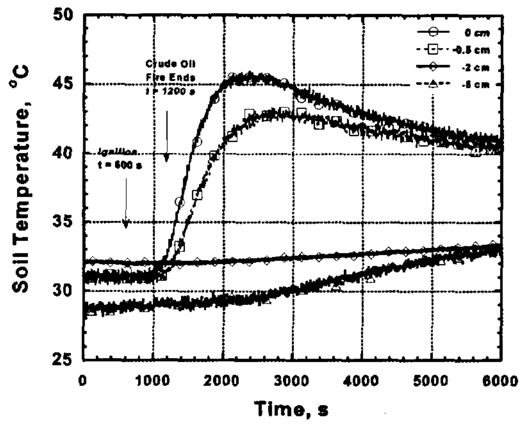

Figure 4. Temperature vs Time for a 700 s *In-Situ* Crude Oil Burn Exposure with *S. Alterniflora* Sod at -2 cm Elevation.

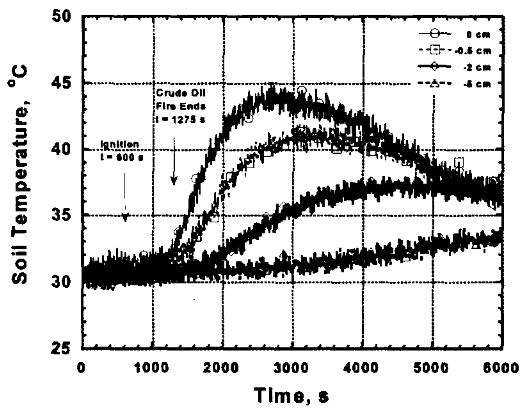

Figure 5. Temperature vs Time for a 700 s *In-Situ* Crude Oil Burn Exposure with *S. Patens* Sod at -2 cm Elevation.

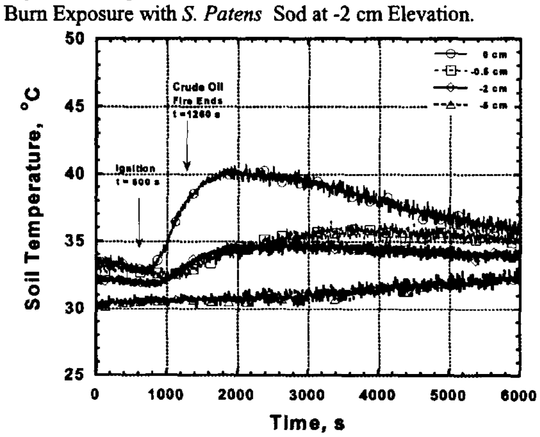

Figure 6. Temperature vs Time for a 700 s *In-Situ* Crude Oil Burn Exposure with *S. Lancifolia* Sod at -2 cm Elevation.

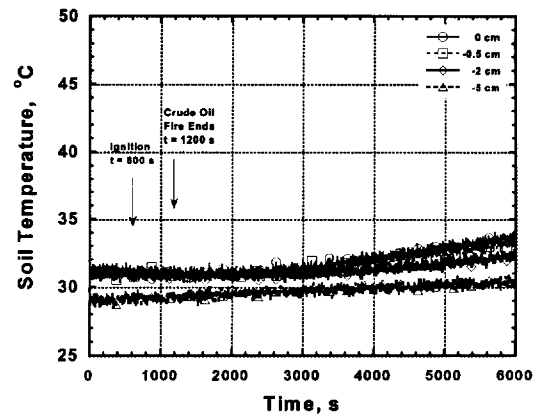

Figure 7. Temperature vs Time for a 700 s *In-Situ* Crude Oil Burn Exposure with *S. Alterniflora* Sod at -10 cm Elevation.

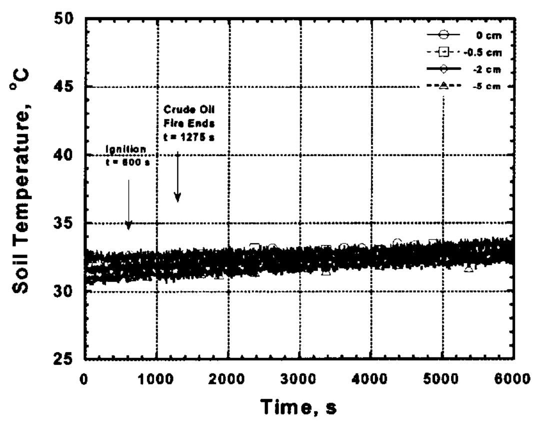

Figure 8. Temperature vs Time for a 700 s *In-Situ* Crude Oil Burn Exposure with *S. Patens* Sod at -10 cm Elevation.

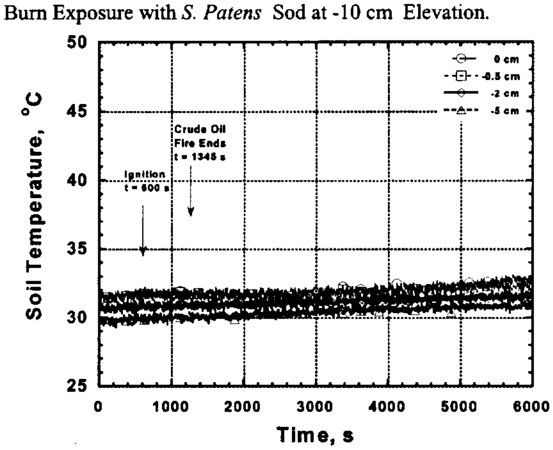

Figure 9. Temperature vs Time for a 700 s *In-Situ* Crude Oil Burn Exposure with *S. Lancifolia* Sod at -10 cm Elevation.

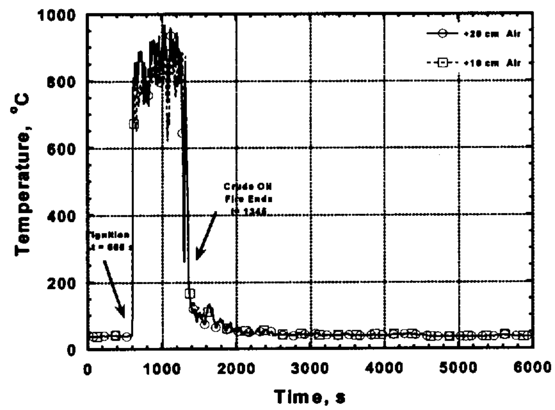

Figure 10. Air Temperature vs Time for a 700 s *In-Situ* Crude Oil Burn Exposure.

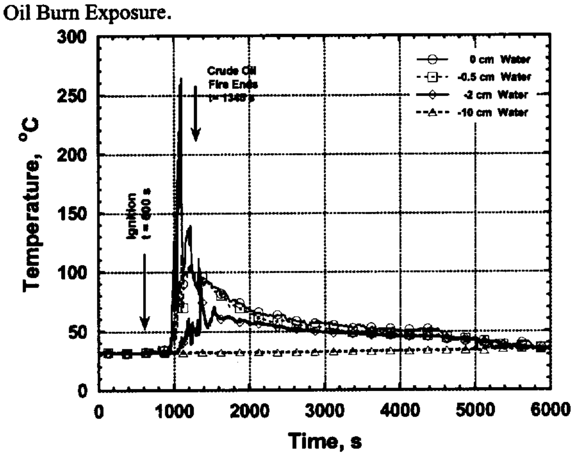

Figure 11. Water Temperature vs Time for a 700 s *In-Situ* Crude Oil Burn Exposure

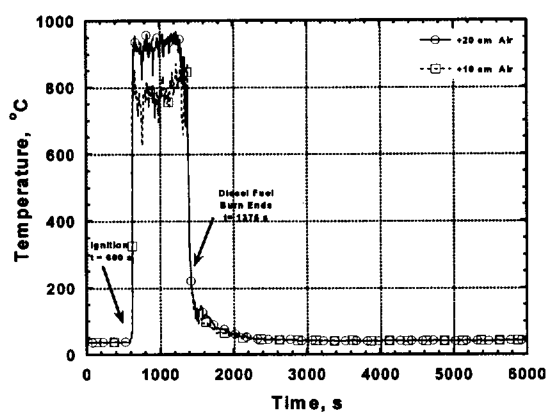

Figure 12. Air Temperature vs Time for a 700 s *In-Situ* Diesel Fuel Burn Exposure.

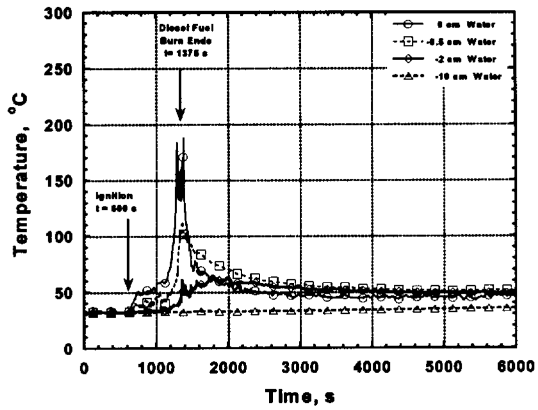

Figure 13. Water Temperature versus Time for a 700 s *In-Situ* Diesel Fuel Burn Exposure.

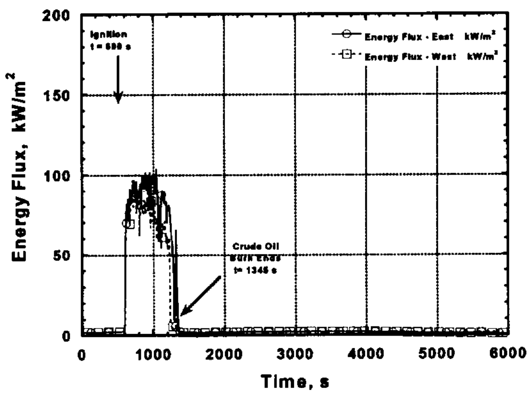

Figure 14. Total Heat Flux versus Time for a 700 s *In-Situ* Crude Oil Burn Exposure.

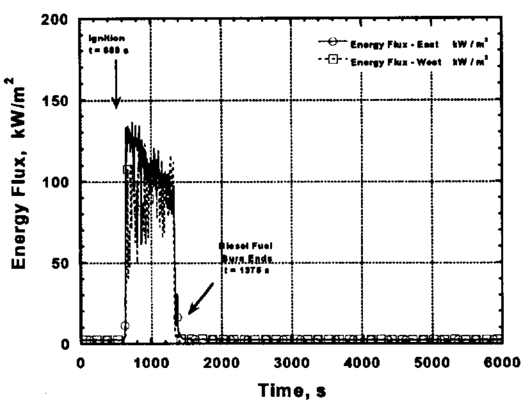

Figure 15. Total Heat Flux versus Time for a 700 s *In-Situ* Diesel Fuel Burn Exposure.

Table 2. Peak Temperatures and Estimated Depth of 60 °C Isotherm for *S. Alterniflora*

Test ID	UnOiled			Oiled		
	+ 2 cm	- 2 cm	-10 cm	+ 2 cm	- 2 cm	-10 cm
Burn 10-1 Peak Temp. °C T/C < 60 °C				A18 103 °C -2 cm	A15 45 °C 0 cm	A40 35 °C 0 cm
Burn 10-2 Peak Temp. °C T/C < 60 °C	A25 96 °C -2 cm	A23 61 °C -0.5 cm				
Burn 10-3 Peak Temp. °C T/C < 60 °C			A28 33 °C 0 cm			
Burn 10-4 Peak Temp. °C T/C < 60 °C	A29 95 °C -1 cm	A1 66 °C 0 cm			A31 45 °C 0 cm	A32 36 °C 0 cm
Burn 10-5 Peak Temp. °C T/C < 60 °C			A27 32 °C 0 cm	A26 424 °C -2 cm	A17 46 °C 0 cm	
Burn 10-7 Peak Temp. °C T/C < 60 °C	A13 99 °C -2 cm	A21 46 °C 0 cm				
Burn 10-8 Peak Temp. °C T/C < 60 °C				A20 96 °C -3 cm	A19 46 °C 0 cm	A33 35 °C 0 cm
Burn 10-9 Peak Temp. °C T/C < 60 °C		A22 43 °C 0 cm				A14 35 °C 0 cm
Burn 10-10 Peak Temp. °C T/C < 60 °C		A38 62 °C -0.5 cm	A11 33 °C 0 cm	A8 96 °C -2 cm		
Burn 10-11 Peak Temp. °C T/C < 60 °C			A30 34 °C 0 cm			
Burn 10-12 Peak Temp. °C T/C < 60 °C					A34 59 °C 0 cm	

Notes: 1) Axxx is *Spartina Alterniflora* plant sod identification number
2) Peak temperature is value reported by thermocouple located at soil surface (0 cm).
3) T/C < 60 °C is depth of thermocouple reporting temperature that did not exceed 60 °C.
4) Uncertainties discussed in Section 3.1

probability that the value would be in the interval ($\bar{x} \pm a$) 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 7. 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

Table 3. Peak Temperatures and Estimated Depth of 60 °C Isotherm for *Spartina Patens*

Test ID	UnOiled + 2 cm	UnOiled - 2 cm	UnOiled -10 cm	Oiled + 2 cm	Oiled - 2 cm	Oiled -10 cm
Burn 10-1 Peak Temp. °C T/C < 60 °C	P51 49 °C 0 cm				P53 45 °C 0 cm	
Burn 10-2 Peak Temp. °C T/C < 60 °C				P54 92 °C -1 cm	P57 37 °C 0 cm	P10 34 °C 0 cm
Burn 10-3 Peak Temp. °C T/C < 60 °C	P61 71 °C -0.5 cm	P59 42 °C 0 cm	P4 32 °C 0 cm	P5 476 °C -5 cm		
Burn 10-4 Peak Temp. °C T/C < 60 °C				P3 400 °C -3 cm		
Burn 10-5 Peak Temp. °C T/C < 60 °C		P65 45 °C 0 cm	P60 33 °C 0 cm			P58 36 °C 0 cm
Burn 10-7 Peak Temp. °C T/C < 60 °C				P44 98 °C -2 cm	P35 41 °C 0 cm	P42 34 °C 0 cm
Burn 10-8 Peak Temp. °C T/C < 60 °C	P56 100 °C -2 cm	P64 36 °C 0 cm				
Burn 10-9 Peak Temp. °C T/C < 60 °C			P62 35 °C 0 cm		P63 45 °C 0 cm	P12 35 °C 0 cm
Burn 10-10 Peak Temp. °C T/C < 60 °C			P9 32 °C 0 cm	P55 97 °C -2 cm		
Burn 10-11 Peak Temp. °C T/C < 60 °C	P7 74 °C -0.5 cm					
Burn 10-12 Peak Temp. °C T/C < 60 °C		P2 42 °C 0 cm			P53 48 °C 0 cm	

Notes: 1) Pxxx is *Spartina Patens* plant sod identification number
2) Peak temperature is value reported by thermocouple located at soil surface (0 cm).
3) T/C < 60 °C is depth of thermocouple reporting temperature that did not exceed 60 °C.
4) Uncertainties discussed in Section 3.1

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 specimen. 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

Table 4. Peak Temperatures and Estimated Depth of 60 °C Isotherm for *S. Lancifolia*

Test ID	UnOiled + 2 cm	UnOiled - 2 cm	UnOiled -10 cm	Oiled + 2 cm	Oiled - 2 cm	Oiled -10 cm
Burn 10-7 Peak Temp. °C T/C < 60 °C						
Burn 10-8 Peak Temp. °C T/C < 60 °C						
Burn 10-9 Peak Temp. °C T/C < 60 °C						
Burn 10-10 Peak Temp. °C T/C < 60 °C						
Burn 10-11 Peak Temp. °C T/C < 60 °C		L39 41 °C 0 cm		L41 628 °C >5 cm		
Burn 10-12 Peak Temp. °C T/C < 60 °C	L48 96 °C -2 cm		L37 33 °C 0 cm			

Notes: 1) *Sagittaria Lancifolia* sods were not included in diesel fuel burns.
2) Lxxx is *Sagittaria Lancifolia* plant sod 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 that did not exceed 60 °C.
5) Uncertainties discussed in Section 3.1

Table 5. Burn Durations, Average Total Heat Flux, and Wind Data

Test 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
10-1	755	116	± 10	109	± 20	1.6	317
10-2	810	116	± 30	89	± 32	2.3	211
10-3	775	107	± 17	88	± 26	2.2	294
10-4	740	99	± 13	88	± 13	2.3	214
10-5	760	122	± 25	99	± 27	2.8	311
10-7	675	93	± 11	102	± 21	1.8	204
10-8	600	69	± 6	117	± 17	2.8	32
10-9	695	66	± 10	63	± 11	1.0	105
10-10	600	66	± 5	106	± 18	1.4	53
10-11	660	71	± 11	71	± 21	2.2	203
10-12	745	84	± 15	68	± 22	1.2	145

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

Table 6 . Average Peak Soil Temperatures and Estimated Depth of 60 °C .

Plant 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
Diesel Fuel					
- 10 cm	770	34	32 to 36	0	0
- 2 cm	770	46	32 to 66	0	0 to -0.5
+ 2 cm	770	91	71 to 103	- 1.5	-0.5 to -2
Crude Oil					
- 10 cm	660	34	32 to 35	0	0
- 2 cm	660	57	36 to 62	0	0 to -0.5
+ 2 cm	660	95	74 to 100	-2	-0.5 to -3

Notes:
* Average Peak Soil Temperature - peak temperature recorded at soil surface thermocouple Values from all plant specimens 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.

fuel/combustion gases should make position much less of a concern with the air thermocouples. This uncertainty analysis assumed that the thermal conductivity or 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 - 18% to + 25 % 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 - 32% to + 22%.

4.0 Discussion

This study exposed 184 specimens of *Spartina Alterniflora*, *Spartina Patens* and *Sagittaria Lancifolia* to a spills of diesel fuel and southern Louisiana crude oil, 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. Fifty years of marsh burning in southern Louisiana has contributed a wealth of experience, but before this experience can be extrapolated to other wetland systems, the relationship between fire conditions and plant recovery must be more fully characterized. Bryner *et al.* (2000) and Lin *et al.* (2001) exposed a single plant species, *S. alterniflora* to a single burning hydrocarbon, diesel fuel, and monitored the plant recovery/regrowth over a period of 7 months. This study builds upon their work by exposing three plant species to both diesel fuel and crude oil burns. The goal of this study is 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 examined 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) different fuels, 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 as 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 and Komarek 1975 Vogl 1967) and to provide better wildlife habitat (Kirby *et al.* 1988, Schmalzer *et al.* 1991). The role that water (or lack of water) plays in protecting the roots of marsh plants is important, 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.

The work of Lin *et al.* (2001) reported that some *S. alterniflora* recovered in sods with the soil temperatures as high as 110 °C and 80 °C at 0 and 0.5 cm below the soil surface, respectively. Therefore, surface soil temperature (0 and 0.5 cm below the soil surface) may not be appropriate to predict thermal effects on plants. Plant reproductive organs, such as rhizomes, are located below the soil surface. In contrast, soil temperatures 5 cm below the soil surface of sods that exhibited regrowth after burning were < 37 °C, which was not high enough to kill the below ground rhizomes. Furthermore, no *S. alterniflora* recovered at temperatures greater than 60 °C at the 2 cm depth. In addition, almost all *S. alterniflora* recovered at temperatures less than 60 °C at 2 cm below the soil surface. It appears that the critical temperature for survival of *S. alterniflora* is 60 °C at a 2 cm soil depth. Since lethal temperatures for most vascular plants have been cited in the range of 60 °C to 65 °C (Byram 1948; Ahlgren 1974; and Levitt 1980), Lin *et al.* (2001) suggest that plant recovery may be predicted based on the temperatures recorded at 2 cm below the soil surface.

This study monitored soil temperatures as a function of water level or soil elevation, soil depth, plant species, and fuel type. Peak soil temperatures, including the average and range of the values, are tabulated in Table 6. At the -10 cm plant elevation, the temperatures recorded at the soil surface did not exceed 36 °C. For plants positioned at the -2 cm, average peak temperatures for the soil surface

Table 7. Uncertainty in Experimental Data.

	Component Standard Uncertainty	Combined Standard Uncertainty	Total Expanded Uncertainty
Soil Temperature			
Calibration	± 1 %		
Position	- 5 % to + 10 %	- 9 % to + 13 %	- 18 % to + 25 %
Repeatability	± 7 %		
Random	± 3 %		
Total Heat Flux			
Calibration	± 2 %		
Zero	-0 % to + 2 %	- 16 % to + 11 %	- 32 % to + 22 %
Soot Deposition	- 12 % 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 + 11 %	- 16 % to + 21 %
Repeatability	± 5 %		
Random	± 6 %		
Plant 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.			

thermocouples was slightly less than 60 °C, but three of the plants did briefly see temperatures of 61 °C , 62 °C, and 66 °C. None of the instrumented plants at -2 cm and -10 cm elevations experienced 60 °C. temperatures below the surface of the soil. Plants that were located at +2 cm above the water did undergo peak temperatures ranging from 71 °C to 103 °C. In order for the soil temperatures to increase significantly above 100 °C, the water in the soil would have to be boiled or evaporated out of the soil. Since the soil temperatures did not typically exceed 100 °C, either the burn exposure was too short to bake out the water or the soil was absorbing or wicking additional water into the exposed soil. Bryner *et al.* (2000) reported that 400 s appear too short of a burn duration for the exposed soil (+10 cm) to reach equilibrium. Longer burn exposures of 1400 s did appear sufficient for exposed (+10 cm) soil to reach equilibrium. Since none of the soil temperatures appeared to level off by the end of the 700 s burn exposures during this study, the exposed soil probably did not reach equilibrium. The wicking action of the exposed soil was not observed by Bryner *et al.* (2000). While wicking occurred at +2 cm of exposed soil and was not observed at +10 cm of soil, it is not clear how high exposed soil will absorb water during an *in-situ* burn. Post-burn exposure observations noted that on four plant sods, the surface of the sod had opened up and caused the thermocouple array to be exposed. These sods, A26, P5, P3, and L41, all reported peak temperatures above 400 °C. Temperatures reported by these "exposed" thermocouple arrays were not included in the average peak temperature or estimated depth of 60 °C values presented in Table 6.

The estimated depth for the 60 °C isotherm was 0 cm or at the surface of the soil for the -2 cm and -10 cm plant elevations. For the +2 cm plants which exposed 2 cm of soil above the water surface, the 60 °C isotherm was estimated to be between -1.5 cm and -2 cm below the soil surface, basically at the same elevation as the surface of the water. As the *in-situ* burn evaporated the water from the soil, the soil may have acted as a "wick" and drawn additional water into the drier soil above the water line. Very few of the plants at -10 cm, -2 cm, or +2 cm experienced a sustained stress of 60 °C temperatures at greater than 2 cm of depth in the soil. Therefore, the work of Lin *et al.* (2001) would predict that thermal stress was insufficient to prevent recovery and regrowth of these plants. Almost all of these plants would be expected to recover from the thermal stress of these *in-situ* burn exposures. As these plants are monitored through at least one growing season, plant recovery/regrowth data will provide additional insight as to whether these expectations are well founded.

Neither plant species or pre-oiling appeared to have significant impact on the soil temperatures. This lack of significant impact would be consistent with the important and perhaps dominant role that water plays in the transfer of energy through wet or moist soil. The presence or lack of water may be the controlling factor for transfer of energy through the soil. For this limited set of 25 *S. alterniflora*, 26 *S. patens*, and 4 *S. lancifolia*, the soil temperatures at comparable soil depths appeared remarkably similar for all of the three species. Although the *S. patens* sods were typically more dense and it was more difficult to insert the thermocouple arrays, this study did not quantitatively characterize sod differences. Qualitatively, the soil in all the sods appeared to have a large organic component. Although half of the instrumented sods were pre-oiled with either diesel fuel or crude oil, there did not seem to be significant differences between oiled and unoiled sods a comparable elevations. Bryner *et al.* (2000) did not attribute any difference in soil temperatures to whether the sod was or was not pre-oiled. As these plants are monitored through at least one growing season, plant recovery and regrowth data will provide additional insight as to whether one species responds better or worse to *in-situ* burn exposure.

Although the burning diesel fuel burns appeared to produce significantly higher total heat fluxes than the crude oil tests, both fuels produced similar soil temperatures. 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 diesel fuel burns and crude oil burns were 100 kW/m^2 and 80 kW/m^2, respectively (Table 5). The values for diesel fuel are similar to the average values reported for burning diesel fuel on water by Walton *et al.* (1999) and Bryner *et al.* (2000). The total heat flux values appeared significantly higher for the diesel fuel burns than for the crude oil burns. However, the difference between the crude oil and diesel fuel generated heat fluxes was about the same magnitude as the differences between the two heat flux gauges which were located on the east and west sides of the tank. Some the differences between the east and west flux values did appear to correlate with the wind direction as was described in Bryner *et al.* (2000). The different burn exposures which resulted from burning diesel fuel or crude oil did not appear to cause significantly different soil temperatures.

4.2 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, the stress on the marsh vegetation can range from short-term depressions of photosynthesis to near total mortality (Alexander *et al.* 1985, Baker 1970, 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.

The experimental design matrix for this series of burns included exposing 64 of the plants to the chemical stress of pre-burn oiling with either diesel fuel or crude oil. The pre-burn oiling was applied 24 hours before each burn and was designed to stress the affected plant specimens, but not kill the plants. The experimental design of Bryner *et al.* (2000) had intended that the pre-oiling be the dominant chemical stressor, but as diesel fuel was absorbed into the soil during the fueling phase of pre-burn operations, this "rogue" oil became the dominant chemical stressor. Lin *et al.* (2001) documented significant amounts of petroleum hydrocarbons in the plants which were positioned at 0 cm and - 2 cm elevations. Even the unoiled plants contained significant amounts of hydrocarbons. Lin *et al.* concluded that while this "rogue" oil was not in high enough concentrations to outright kill the plants, its concentration was high enough to prevent regrowth.

In order to prevent the rogue oil contamination of the plant sods, the +2 cm plants were collared, the -2 cm plant water lines were manually adjusted instead of using access holes (Bryner *et al.* 2000), and each plant sods was flushed with clean water before removal from the burn tank. The 10 cm collars which were fitted into the top of the 20 liter container were designed to reduce splashover of fuel into the container during the burn exposure. Since the steel collars extended about 10 cm above the water surface, the collars would reduce the amount of radiation from burning fuel adjacent to the container. However, this reduction was expected to be relatively small as compared to the radiation from the hot layer just above plants. Instead of allowing the water level to equilibriate through small access holes that were drilled into the side of the container of the -2 cm plants, water was added manually to each sod to insure the water level inside the container was the same as the main burn tank. Each container had a drain tube which was located at the bottom of the sod container, typically at least 20 cm below the water surface. This drain was checked before burn exposure to insure exchange of water between the plant sod and the main tank. This insured that if water was evaporated away during burn exposure, additional water could be drawn into the container during the burn exposure.

After each burn exposure, each sod was gently flushed with clean water to prevent burn residue from contaminating the soil. The burn residue of a diesel fuel burn was typically an oily liquid and was easily floated away from the soil and plant stubble. Crude oil residue was a mixture of tar and sooty residue which congealed as it cooled. The tar residue was sticky and clung to the stubble of the plant stems even after the water was drained from the container. The changes to the experimental procedure, including the collars and the post burn flushing, appeared to reduce the contamination via rogue oil.

In-situ burning of crude or refined hydrocarbons offers spill response teams an alternative tool which may utilize in order to minimize the impact of spilled oil within a wetland environment. In addition to removing much of the spilled oil, intentionally burning the oil in place can prevent the spilled oil from spreading to additional areas. 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. Marsh plants such as *S. alterniflora*, *S. patens*, and *S. lancifolia*, may be protected from the thermal stress if the water layer above the soil is at least 2 cm thick. 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

One hundred and eighty-four specimens of *S. alterniflora*, *S. patens*, and *S. lancifolia* 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 or crude oil 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 demonstrate that 10 cm of water over the soil line is definitely sufficient to prevent permanent damage to plants. A layer of water, just 2 cm deep provided enough thermal protection to limit peak temperatures at the soil surface to less than 70 °C. Only when the soil line is above the water line did the soil temperatures consistently exceed the 60 °C range where plant survivability data suggest permanent damage begins to occur. For plant specimens which were positioned 2 cm above the water level, the 60 °C isotherm appeared to penetrate about 2 cm below the soil for the diesel fuel burns and between 2 cm and 3 cm below the surface crude oil burns. The plant recovery and regrowth data of Lin *et al.* (2001) suggest that *S. alterniflora* plants are likely to recover if the 60 °C isotherm penetrates less than 2 cm below the soil surface.

Diesel fuel and southern Louisiana crude were burned to expose three different plant species to the thermal and chemical stress of *in-situ* burning. The total heat flux values recorded during the diesel fuel burns appeared to be significantly higher than for the crude oil burns. But, both fuels appeared to result in similar soil temperatures in all three plant species for comparable plant elevations. Pre-oiling the plant sods did not appear to impact the soil temperatures. The total heat flux data confirms that these burns were large enough to simulate the heat flux and temperature of full-scale fires.

But, 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 64 of the plant specimens. Modifications to the burn procedure appeared to reduce "rogue" oil contamination of the plant sods. As the plants are monitored through a growth cycle (May 2001), the 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 and crude oil burns which exposed three common marshland plant species, *S. alterniflora*, *S. patens*, and *S. lancifolia* to simulated *in-situ* burns, the soil temperature data indicates that a 2 cm layer of water may provide sufficient protection from permanent damage to the plant/root system. 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 different 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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