Combustion of Floating, Water-in-oil Emulsion Layers Subjected to External Heat Flux

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Abstract

Prior studies have shown that emulsions with greater than a certain amount of water do not burn, and thus present a difficulty in applying in-situ combustion techniques. It is also known that, when a normally incombustible material is subjected to a certain minimum heat flux, it can be ignited, and a sustained fire and flame spread can be achieved. This principle is applied to oil spill and emulsion combustion, so that, the window of opportunity for the application of in-situ burning as a primary response countermeasure for oil spill cleanup can be widened, even in the difficult situations like a spill confined by ice.

In this paper we present results obtained from several burn tests with pools of water-in-oil emulsions for diesel and Milne Point (MPU) crude floating on water. Some results are also presented for emulsions of Alaska North Slope (ANS) crude. The diesel emulsions ranged from 20 to 80 % water content, crude oil emulsions ranged from 0 to 40 % water content, and the external radiant heat flux ranged from 0 to 14 kW/m^2. Measurements included the threshold (minimum) heat flux needed to achieve sustained burning of the emulsion, average burning rate, and residue thickness. It was interesting to observe that emulsion burning is very sensitive to the external radiation heat flux. Below a certain threshold heat flux ignition is impossible, but slightly above that flux, emulsions burn very well, with reasonable removal efficiency.

1. 0 Introduction

In-situ oil spill combustion can be a highly effective clean up measure for contained spills occurring on open water bodies, such as an oil spill on the ocean contained by booms or a spill surrounded by ice. When feasible, it is an inexpensive technique that can have a very high efficiency of removal (possibly greater than 99%), and the spill removal rate is very rapid compared to those of mechanical means. Also, ecological damage from the spill combustion has been found to be less severe compared to that from conventional methods. (Fingas and Laroche, 1990; Evans and Tennyson, 1991). However, the window of opportunity for applying the technique is often limited for several reasons. For example, the wave and wind conditions may be too severe for ignition, the spill may be too close to populated areas, or the oil may mix with water to form emulsions that are difficult to ignite or burn. Extensive studies by Buist and McCourt, 1998, Bech *et al.*, 1992, Guenette *et al.*, 1994, and Guenette *et al.*, 1995 have shown that stable emulsions with greater than a certain amount of water do not burn.

It has been known in the field of fire research that several materials, such as most woods and certain plastics, do not sustain fire on a small scale unless assisted by external heat flux. A large fire returns a significant amount of heat back to the

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burning area and also to the yet-to-be–ignited area, allowing fire to sustain and spread. Prior work shows that, when a material (normally incombustible in the absence of external heat flux) is subjected to a minimum (also known as threshold or critical) heat flux, it can be ignited, and a sustained fire and flame spread can be achieved (Brehob and Kulkarni, 1998). In the present work, this principle is applied to the oil spill and emulsion combustion problem. If successful, the window of opportunity for in-situ combustion of emulsions can be widened.

The important question to ask is, how can an emulsion pool be subjected to external heat flux when it is floating on an open water body? Among other possibilities, it is proposed here that the external heat flux may come from an adjacent pool fire as shown in Figure 1. A small pool fire will not produce sufficient heat flux, but if the pool size is sufficiently large, it will provide the needed minimum heat flux for the surrounding emulsion to ignite and burn. This will make the pool size and fire size grow, provide an even larger heat flux to the yet-unburned emulsion around the pool, cause the mixture to ignite and continue to burn, and the process will continue. *Thus, the emulsion layer, which was considered noncombustible, can now be burnt with this technique.*

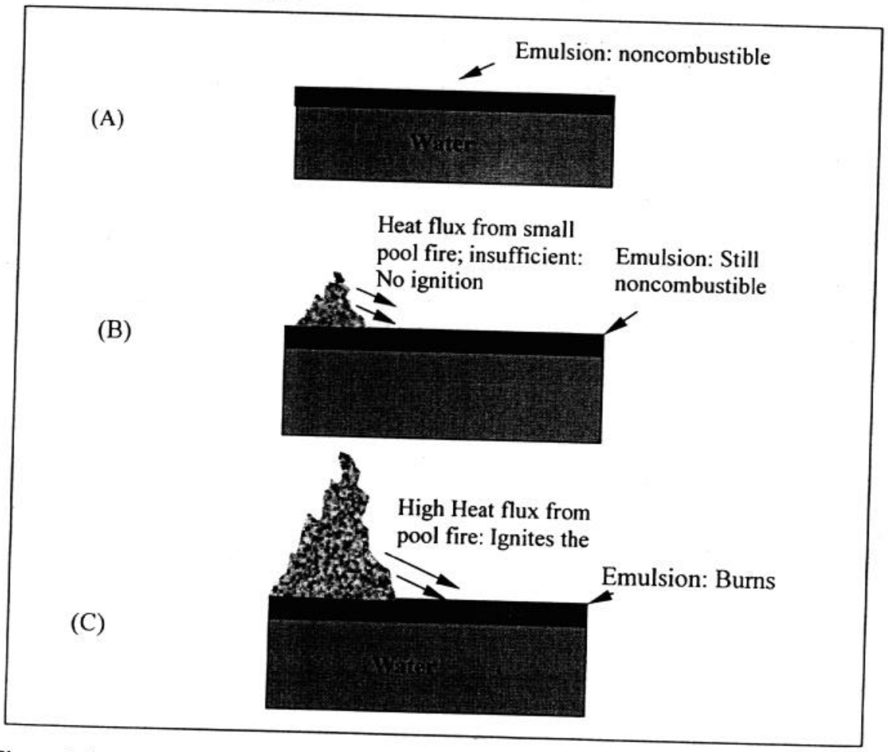


Figure 1 A noncombustible oil-water emulsion (A) can not be ignited with heat flux less than the threshold heat flux value (B), but it may be ignited with high heat flux from an adjacent pool fire of sufficiently large size (C).

The initial pool fire of desired size might be achieved by one of several different means, such as, intentionally starting a fresh oil fire, using a special large size igniter, using artificial external heat flux, etc. Correlation of the radiant heat flux as a function to the surrounding area of the fire size depends on the type of fuel and other factors, such as how much soot the flames produce and the height of flames. Heat feedback from a known size of pool fire to its base has been modeled (see, for example, Tien, 1985), and measured for large fires (see, for example, Yamaguchi and Wakasa, 1986).

The scope of the current work is limited to studying the ignition and combustion behavior of emulsions under external heat flux. The size and other characteristics of adjacent fires that may supply the heat flux will be a subject of later investigation (which has also been discussed to some extent in the literature). The specific objective of the current work is to conduct burn tests on emulsion pools of diesel and Milne Point (MPU) crude, and some limited testing on Alaska North Slope (ANS) crude, for a range of external heat fluxes and water content in the emulsions. These three fuels were selected because they have been studied extensively by Buist and McCourt, 1998 in similar types of experiments but with no external heat flux. Measurements include the threshold (minimum) heat flux needed to achieve sustained burning of the emulsion, burn period, average burning rate, and residue volume.

2.0 Experimental

The set up was designed and instrumented to take data from a pool fire of water-in-oil emulsion floating on top of water. The schematic of the pool fire set up is shown in figure 2. A 28 cm x 28 cm size pool was placed in the center of a 150 cm x 120 cm x 25 cm deep water pool. The central pool is contained inside the outer pool by metal bars. The emulsion is poured in the center pool to a desired thickness on top of the water to produce a 15 mm fuel layer. The outer water pool is needed for protection from accidental spillover and flame spread from the fuel. For visual accessibility to the fire, the outer tank is made of clear acrylic. Emulsions of different oils and various compositions were made using a separate custom built apparatus based on the technique of end-over-end rotation (Hokstad *et al.*, 1995) of cylinders containing water and oil mixtures of desired proportion for up to 48 hours.

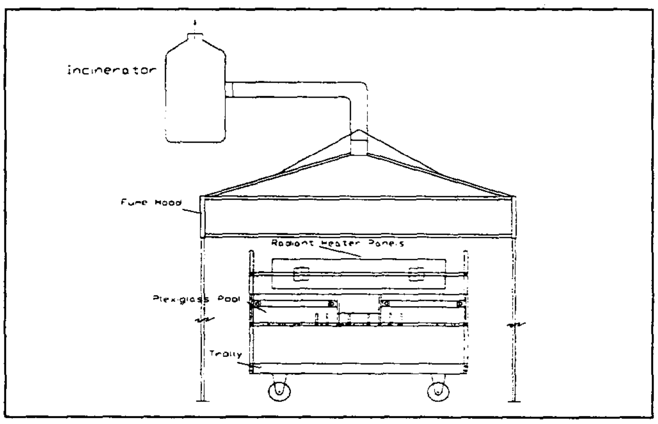


Figure 2. Schematic of Pool Fire Set-up

Two electrically operated heating panels were used to supply external radiation. The panels have rows of heating elements embedded in a ceramic material and have a Corning Vycor face plate. They are electrically heated by 440 V, three phase, 60 amp power and controlled by a silicon control rectifier (SCR), which allows the panels to reach a maximum temperature of 815 °C that produce a maximum radiative heat flux of about 60 kW/m^2 at the panes. The panels were mounted facing toward the pool at an angle of 30° to vertical to irradiate the oil/emulsion pool with a uniform heat flux. Based on the geometry and view factor estimated, the fuel pool was subjected to a radiative heat flux of up to 22 kW/m^2. Depending on the requirements, as the experiments progressed, this maximum radiative heat flux level was changed by raising or lowering the panels. Calibration of the heater panels was made using a 12.7 mm diameter, water-cooled circular foil heat flux gage. For the calibration, twelve locations were chosen to cover the emulsion pool surface and measurements were taken at steady state. The average of the twelve readings for a particular setting of the controller was considered as the heat flux on the emulsion pool surface at that controller setting. The maximum and minimum heat flux measurements for any particular setting were within ± 5 % of the average heat flux value at that setting.

The entire pool assembly was mounted on a movable base and covered with a flame hood. The hood outlet was connected to a down-fired combustor (DFC) through an electric blower. The exhaust of the pool fire was burned in the DFC. Ignition of the pool was achieved by use of either 11 in long matchsticks supported at the front end of a wooden rod or a small natural gas pilot flame close to the emulsion surface.

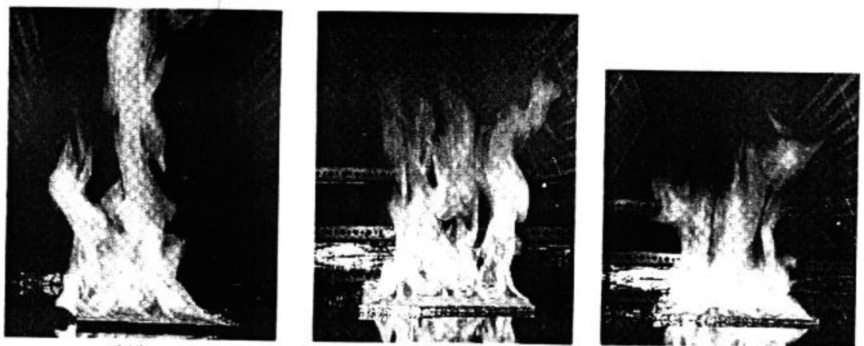
Type K thermocouples were used to monitor the in-depth temperature distribution and temperature at the oil-water interface. A rake of five thermocouples with a spacing of 5 mm between consecutive thermocouples was mounted inside the inner pool. A 16-channel data acquisition board was used to collect the temperature data during the burn and the data was stored on a PC.

A video camera was used to record the test runs. These measurements were needed to determine the flame height, the conditions at which ignition took place (or did not take place), provide input to numerical models, and in general, understand the interdependence of the variables (for example, the relation between heat flux and burn rate). The data will also be used to generate dependence of average flame height on various other factors, such as water content of the emulsion, weathering, and incident radiant heat flux. The flame height data can in turn be related to the heat flux distribution on the pool surface surrounding the fire.

In a typical test run, a predetermined amount of emulsion was poured evenly over the center section of the water in the pool fire set-up shown in figure 2. The radiation heater panels were then turned on to a known heat flux setting with the emulsion pool covered so that the pool did not receive any heat flux till the panels reached steady state. It was noted during the heater panel calibration that the panels reached steady state in about 5 minutes after being turned on. The pool was uncovered and exposed to the panel radiation after the panels were at steady state. After the surface temperature reached a certain preset value, an attempt was made to ignite the sample. Upon failure to cause ignition, the heat flux level of the panels was increased by a small amount. The process was repeated until sustained combustion was achieved, and the minimum or critical heat flux needed to ignite the sample was noted. When the fire extinguished, the volume of the residue was measured. Based on the initial volume of emulsion poured and the total time of burn, the average oil burning rate value was calculated.

3.0 Results

Burn tests were conducted with emulsion pools of diesel, Milne Point (MPU) crude, and Alaska North Slope (ANS) crude. These three fuels were selected because they have been studied extensively by Buist and McCourt, 1998 in similar types of experiments but with no external heat flux. The results presented are for the fresh oils. Weathering is known to affect emulsification significantly (Buist and McCourt, 1998), and that study is planned in the future. The three oils differ in burning and emulsification characteristics. Figure 3 shows fire from burning fresh oils (not weathered or mixed with water). Diesel takes the longest to ignite and it produces the most soot among the three oils tested. ANS crude ignites almost instantly and it has the tallest flames. The Milne Point (MPU) crude has the shortest flames and produces the least amount of soot. Diesel and ANS crude do not form stable emulsions even after vigorous mixing for 48 hours and therefore, a small amount of either SAE30 motor oil (10% by volume) or MPU crude (5% by volume) had to be added to the mixture to promote emulsification. MPU mixed with water very quickly (less than 8 hours) to form a very stable emulsion. Stability was determined by how long the emulsion holds without breaking; the unstable emulsions separated into water and oil quickly. The emulsion was considered to be stable if there was no visible separation of the water and oil phases of the emulsion by the time the test run was over. It should be noted that the emulsions were probably not "truly"stable, in the sense that they would not last several days or months without separating. However, in a practical situation of an oil spill on ocean, one may expect partial emulsification to take place before applying the spill combustion technique. In a typical test run, the emulsion was used in about 24 hours after it was made.



(A) (B) (C)

Figure 3. Fires produced by burning fresh ANS (A), Diesel (B), and MPU (C).

The critical heat flux values were estimated to have an uncertainty of about ± 0.6 kW/m^2 in addition to a non-uniformity of $\pm$ 5% around the mean values reported. The scatter in data best indicates the overall uncertainty in other experimental values. It is estimated to be about 4% for the burn time measurements, 11% for the residue thickness measurements and 9% for the burn rate measurements.

Figures 4 and 5 show the variation of the minimum heat flux value required to cause the sustained combustion of the emulsion as a function of the water content of the emulsion for diesel and MPU crude, respectively. The heat flux value plotted is the average heat flux incident on the surface of the emulsion pool. Error bars indicate a variation from the average heat flux value at the surface. The minimum heat flux necessary to cause sustained fire increased with increasing water content of the emulsion. It was noted that the MPU emulsions needed greater heat flux to burn compared to the diesel emulsions of same water content. ANS-water emulsions up to 40 % water did not need any external heat flux for ignition and sustained burning. These are very interesting results because they show that normally incombustible emulsions can be made to burn if there is sufficient external heat flux, and thus the window of opportunity for use of in-situ burning technique can be widened.

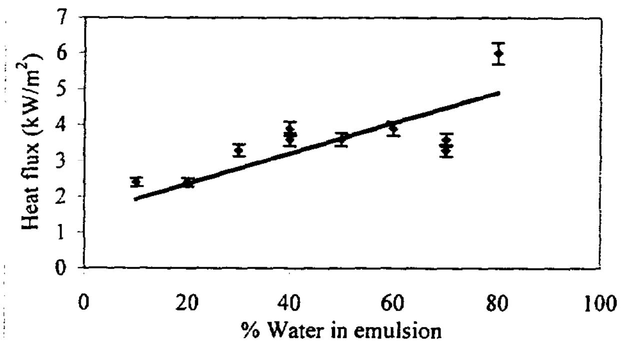


Figure 4. Minimum Heat Flux Required to Cause Sustained Fire as a Function of Water Content of Diesel-Water Emulsion.

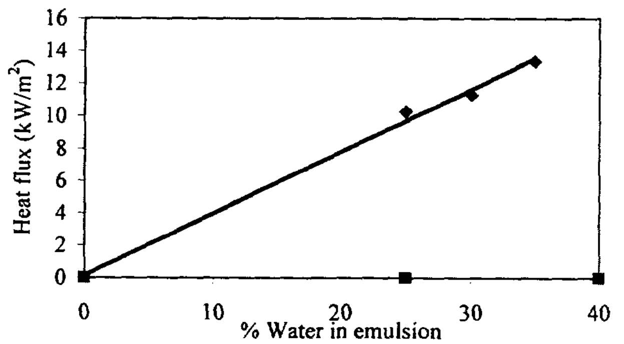


Figure 5. Minimum Heat Flux Required to Cause Sustained Fire as a Function of Water Content of MPU-Water and ANS-Water Emulsions.

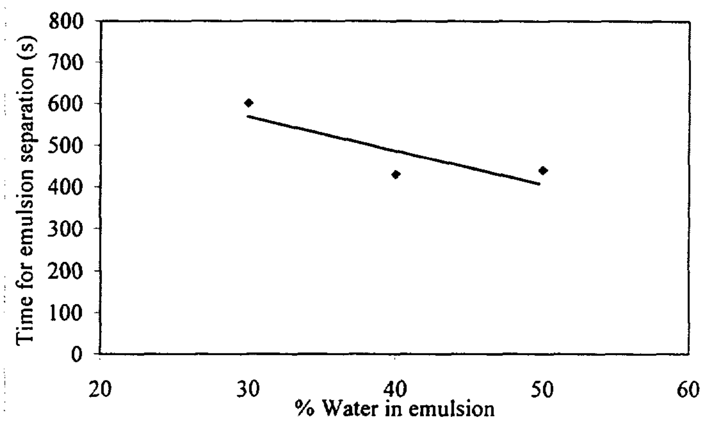


Figure 6. Time for Emulsion Separation as a Function of Water Content of the Diesel-Water Emulsion at Critical Heat Flux.

Figure 6 shows the time for emulsion separation as a function of water content of the emulsion for diesel. These results were obtained at the external heat flux value equal to the critical heat flux. Here, 90 °C was used as the emulsion separation temperature, and the time it took for the top surface of the emulsion to reach 90 °C was noted. The separation temperature was based on experimental observations made in our lab tests (Pisarchik *et al.*, 1997). Guenette *et al.* (1995) have argued that is the oil vapor, not the liquid oil itself, which actually burns. Thus, the ignition delay includes the total period required to heat the emulsion, separate it into oil and water, heat the oil to evaporation temperature, evaporate the oil, mix the vapor and oxidizer from air, and then start the combustion reaction of the mixture. The largest fraction of time in the ignition delay is probably up to the separation of emulsion into oil and water. Thus, the emulsion separation period is closely related to the ignition delay. The ignition delay itself was not calculated, nor measured, because the ignition delay was hard to define precisely in the present setup. It will be somewhat dependent upon the position of the igniter (because the process is not strictly one-dimensional) and the "flashing" phenomenon occurring before sustained ignition.

Figure 7 shows the time for emulsion separation as a function of water content of the emulsion at a constant incident heat flux of 8 kW/m^2 for diesel. At a constant external heat flux, time for emulsion separation increases with increasing water content of the emulsion. The probable reason is, as the water fraction of emulsion increases, the thermal diffusivity of the emulsion layer increases. This means that the emulsion layer is now conducting more of the heat received. Thus it takes more time for the surface temperature to reach the emulsion breaking temperature.

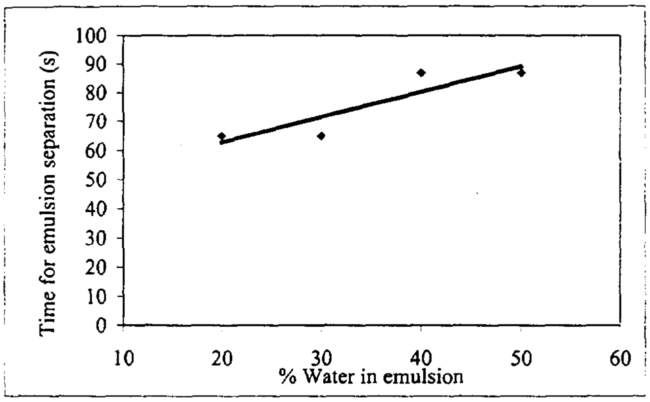


Figure 7. Time for Emulsion Separation as a Function of Water Content of the Emulsion at a Constant Heat Flux of 8 kW/m^2.

Figure 8 shows the average burning rate for diesel as a function of water content of the emulsion at critical heat flux. Overall, the average burning rate decreases with increasing water content of the emulsion. The average burning rate at critical heat flux is a combination of two opposing factors. With more water in the emulsion, there is less amount of diesel separated from the same amount of emulsion. Thus the diesel available for burning is provided at a slower rate from the emulsion layer. Hence the diesel-burning rate is lower. However, the critical heat flux itself increases with increasing water fraction (see figure 4), enhancing the rate of emulsion separation into diesel and water. The net effect, as shown in figure 8, is to somewhat slow down the burning rate with increasing water fraction of the emulsion at the critical heat flux.

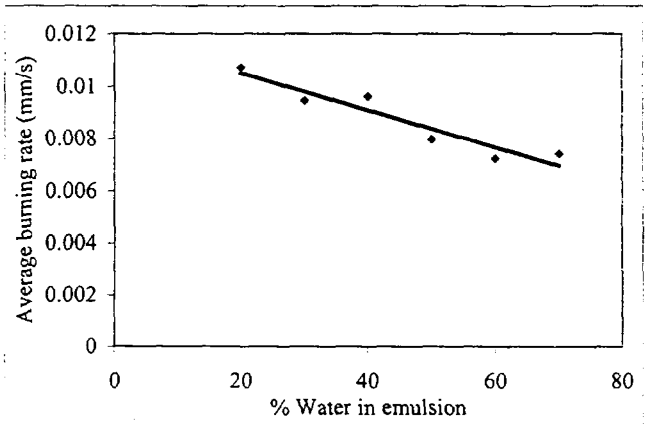


Figure 8. Average Diesel Burning Rate as a Function of Water Content of the Emulsion at Critical Heat Flux.

Figure 9 shows the experimentally measured diesel residue thickness values as a function of water fraction of the emulsion. The residue thickness decreased with increasing water fraction in the emulsion. With more water in the emulsion, there was less diesel to start with. Hence the diesel residue decreased with increasing water fraction of the emulsion.

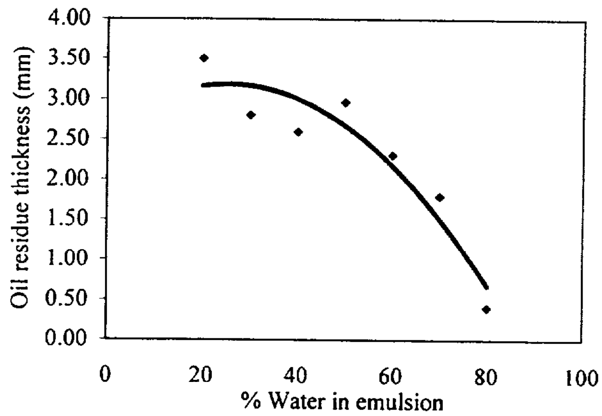


Figure 9. Diesel Residue Thickness as a Function of Water Content of the Emulsion at Critical Heat Flux.

4.0 Summary and Conclusion

Experimental results are presented for several burn tests on pools of water-in-oil emulsions for diesel and Milne Point (MPU) crude floating on water. Some results are also presented for emulsions of Alaska North Slope (ANS) crude. Burn tests were carried out with a range of external heat fluxes and water contents in the emulsions. The diesel emulsions ranged from 20 to 80 % water content, crude oil emulsions ranged from 0 to 40 % water content, and the external radiant heat flux ranged from 0 to 14 kW/m^2.

It was interesting to observe that the emulsion burning is very sensitive to the external radiation heat flux. When normally incombustible emulsions are subjected to a certain minimum heat flux, they can be ignited, with a sustained fire that allows high removal efficiency. Diesel emulsions with up to 80 % water can be burned if external heat flux is at least 6.0 kW/m^2 and MPU crude emulsions with up to 35 % water can be burned if external heat flux is at least 13.4 kW/m^2. The experiments suggest that the window of opportunity can be widened for the application of in-situ burning as a primary response countermeasure for oil spill cleanup. Larger scale experiments are needed to further verify the practical application these conclusions.

5.0 References

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6.0 Acknowledgements

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