

# Remediation of Produced Water Ponds and Associated Crude Oil-Impacted Soil, Wafra Oil Field, Kuwait

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## ABSTRACT

This paper describes a novel, multi-year approach to optimizing the remediation of >2 million m<sup>3</sup> of impacted sand in a complex environmental setting, while meeting stringent international risk guidelines. Historically, 380 hectares of above-grade evaporation ponds were used to manage produced water at the Wafra Oil Field. To facilitate closure of these ponds and associated crude-oil impacted soils, a risk-based cleanup was selected wherein the former pond areas were reclaimed using soils which were temporarily stored as stockpiles after stabilization and sampling. A risk assessment conducted for the site identified 3.2% total petroleum hydrocarbon (TPH) as a cutoff protective of human health and the environment. To optimize remedial design, soils were categorized into two types based on TPH concentration, 1 to 3.2% TPH (Type B) and <1% TPH material (Type A). Laboratory analytical data from a stockpile characterization were correlated with field test-kit and color analyzer measurements to develop a simple field TPH measurement tool. Then statistical analysis coupled with computation of soil volumes and three-dimensional modeling was used to describe the spatial distribution of soil Types A and B in the stockpiles. Next a redistribution strategy was developed to meet international remedial goals. Quantification of spatial TPH distribution in the five stockpiles allowed streamlined hauling distances to the former impoundment locations, while use of real-time global positioning system (GPS) survey data of stockpile reduction, in conjunction with geographic information system (GIS) applications, allowed for accurate calculation of volumes excavated and placed as backfill. Integration of sophisticated computer technology into overall project design optimized environmental engineering, while the GIS methodology also tracked real-time progress and provided final documentation for the project.

**Keywords :** soil remediation, risk-based cleanup, geographic information system, optimized environmental engineering

## 1 INTRODUCTION

The Wafra Oilfield is located in the Partitioned Zone near Kuwait's southern border with Saudi Arabia. Here produced water was historically managed in open, above-ground evaporation ponds. This was a normal and accepted practice not only in Gulf Cooperation Council (GCC) states but in many oilfields worldwide. At Wafra, with water cuts increasing from decades of oil production, the size of the pond area needed for effective evaporation also increased significantly. Associated part per million levels of crude oil entrained in the produced water and floating on the surface of the ponds resulted in decreased evaporation rates and further increased the need for expanding the evaporation areas. Ultimately a total of 41 ponds covering approximately 380 hectares were constructed in the Wafra main gathering center area (Fig.1). The evaporation ponds were generally rectangular with various perimeter lengths but ranging from approximately 20,000 m<sup>2</sup> to over 100,000 m<sup>2</sup> in area. The majority of the ponds consist of a single banded area surrounded by an earthen berm measuring 3 m to 4 m above the surrounding ground level.

In 1999, Joint Operations - Wafra (WJO), a partnership between Kuwait Gulf Oil Company and Saudi Arabian Chevron, developed and implemented a voluntary environmental master plan to eliminate discharge of produced water into the

above-ground evaporation ponds or pits. The intent of this multi-faceted Zero Discharge Initiative was to decommission the pits with minimal impact to the environment, human health, and operations. Key elements of this complex initiative involves: altering oilfield operations by re-injecting produced water for formation pressure maintenance as well as disposal; construction of necessary produced water injection wells, water management facilities and pipeline networks; skimming and consolidation of oil from the surface of the pits including consolidation of oily viscous liquids (OVL) for treatment and recovery into production, construction of a necessary OVL thermal treatment facility; closure and reclamation of the pits; and management of residual oily impacted-sand and sludge in accordance with Kuwait environmental standards and other internationally recognized standards and practices. Multiple Environmental Impact Assessments have been submitted to Kuwait EPA during various phases of the pit remediation work.

The focus of this paper is the novel methods developed and utilized during the environmental remediation project associated with remediation of the residual oily impacted-sand generated during decommissioning of the pits and restoration of the former evaporation pit area. Sequencing of remedial activ



Fig. 1. Wafra Main Gathering Center area indicating evaporation pond boundaries and stockpile locations.

ities included initial unexploded ordnance clearance possibly present from the 1991 Gulf War invasion. Next, free liquids were removed recovering crude oil from the pits, and consolidating OVL and sludge. Pit deconstruction using heavy equipment followed with a total volume over 2 million cubic meters of residual impacted-sand managed into 5 separate stockpiles. Extensive data was collected for determination and selection of the environmental remedy, including lateral and vertical characterization of the stockpiled materials (Fig.2). Through this rigorous site characterization process, analytical laboratory results indicated that the majority of the impacted-sand contained <1% Total Petroleum Hydrocarbons (TPH) (reported as C5 to C35). Further, a third party reviewed human health risk assessment using internationally accepted methodologies, determined that all of the stockpiled material was below TPH Criteria Working Group [1] risk based screening levels (RBSL).

## 2 SITE CHARACTERIZATION AND DECISION METHODS

Over 800 samples have been collected in relation to the remediation activities and analyzed for TPH, other specific carbon-chain ranges of petroleum hydrocarbons, metals, salt, and other analyses. From a toxicology and risk assessment perspective, it was determined that TPH and salinity were the primary drivers of remedial decision making.

One factor for success of the remediation project is the rapid analysis of samples collected in the field. In order to provide the necessary data turn-around, field analytical methods were investigated and tested against regulatory-approved analytical techniques. Such Demonstrations of Method Applicability (DMA), [2] were performed for both the PetroFLAG™ TPH field test kits and a hand-held color analyzer (Anaheim Scientific H500). The PetroFLAG™ kits follow a United States Environmental Protection Agency (USEPA)-documented protocol (SW-846 Method 9074) [3] for measuring petroleum hydrocarbons in soils. The use of a hand-held color analyzer is a novel approach applied specifically for this project as an optimization technique.

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The DMAs were based on selecting samples that represent the range of TPH concentrations anticipated at the site and splitting the samples for analysis by the field methods and a fixed laboratory. Statistical regressions were performed to determine how well the field methods correlated with laboratory results. Prediction Intervals (PI) were constructed from the regressions to determine the uncertainties associated with the comparison of the methods. By plotting how the upper and lower PIs intercept the laboratory-based 10,000 mg/kg action level on the PetroFLAG™ axis (54,500 and 32,400 mg/kg, respectively, (Fig.3), it can be determined which field-based results indicate, within specified levels of confidence, soils that are either above or below the action level, or within an “uncertain” range. Depending on the economics of the project (for example, if costly off-site transport and treatment/disposal were being applied), it could be beneficial to submit samples that field results place in the uncertain interval to a laboratory for confirmation. However, given that on-site treatment and placement is being applied for this project, the economics allow for the material that falls in the uncertain range to be conservatively assumed to be above the action level and managed accordingly. This procedure also allows for the application of a very conservative field-based action level.

The hand-held colorimeter (color analyzer) provided color data in both the red-green-blue (RGB) and the hue-saturation-luminosity (HSL) color scales. Regression analyses indicated that luminosity values were the best predictor of laboratory TPH results. This is expected when measuring the concentration of a dark crude oil contrasted with a light-colored sand matrix. To establish a linear relationship and predictive model between luminosity values and laboratory TPH measurements, it was necessary to perform the mathematical regression analysis with log-converted laboratory results. Initial data indicated that a luminescence value of 75 was associated with the upper PI of the laboratory-based action level (Fig.4). When additional data were acquired and added to the analysis, the luminescence value fell to 65, indicating that the initial value used was conservative, and that the DMA is robust.

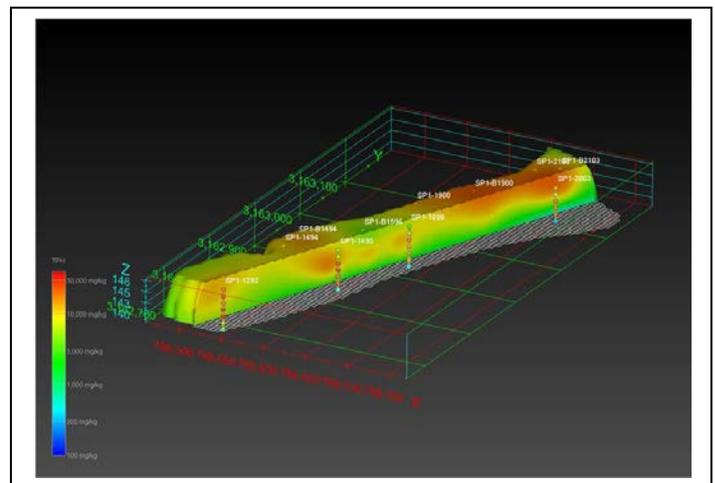


Fig. 2. GPS/GIS 3-dimensional geochemical model of stockpile, colors indicate TPH concentrations. Red = >10,000 mg/kg, blue = <1,000 mg/kg.

Key decisions to be made in the field are whether or not sufficient data have been obtained to determine if the stockpiles and backfill areas have been sampled adequately, and validation that the field and laboratory data relationships remain consistent. As the project proceeds additional data will be collected to expand the PetroFLAG™ and colorimetry DMAs. For DMAs based on correlation, between 10 and 20 samples is considered acceptable [2]. Rather than strictly define specific sample locations and analytical protocols, to further optimize the process, the sampling and analysis plan was based on field analytical results for TPH to allow rapid turnaround of data in guiding subsequent sampling activities. Sample splits from selected samples representing the range of observed TPH values were submitted to a fixed analytical laboratory for confirmatory TPH analysis and regression analysis was applied to establish the relationship between the two data sets, guiding future remedial activities at the site.

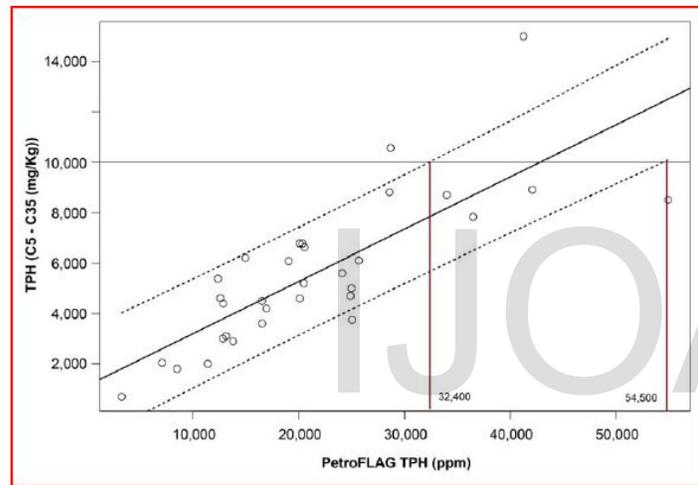


Fig.3. Correlation between field PetroFlag™ data and laboratory TPH results with prediction intervals.

### 3 ENVIRONMENTAL ENGINEERING REMEDIAL DESIGN

The main objectives of the Wafra pit remediation engineering design is to balance the earthwork volumes and to return the desert environment to its natural state while meeting the backfill optimization goals. The main gathering center (MGC) grading limits encompass an area of approximately 380 hectares. Utilizing the existing stockpile volume calculations, field topographic survey, and estimating the final evaporation pit deconstruction impacted sand volumes, a grading plan was created for the MGC. The grading plan incorporates the new design into the existing topography, while limiting the backfill within the boundaries of previous evaporation pits and facilitating effective stormwater drainage.

The primary objective of the stormwater management plan is to preserve and enhance the natural values of the region's topography while accommodating oil field operations. By managing the stormwater runoff from the site, soil erosion will be controlled, flooding of the main access roads will be minimized, and the high soil salinity will be reduced within the

project area.

The stormwater management plan will work in conjunction with a re-vegetation project planned for the site. The establishment of new vegetation will aid in soil stability and increase rainwater infiltration; therefore, decreasing stormwater runoff. The stormwater management plan will also aid in establishment of new vegetation by limiting flooding potential and providing protection from wind erosion during the plant establishment period.

Contributing drainage basins to the Wafra Oil Field are large and are capable of producing excessive amounts of runoff. This has historically resulted in localized flooding. The existing topography was formed with large depressions, which results in standing water during the winter rainy season. Kuwait receives intermittent rainfall during the winter months with ephemeral flowing streams; therefore, desert drainage basins are not always clearly differentiated within the landscape. While flooding will be difficult to eliminate in all areas, a carefully planned and executed stormwater management plan will mitigate consequences of the heavy winter rains.

### 4 SOIL VOLUME CALCULATIONS AND STOCKPILE DISMANTLING STRATEGY

Beginning with the 2008 site characterization efforts, an enhanced GIS/document management system was used to manage all data generated for the project. This system provides a graphical interface for environmental data sets that enables complex spatial and temporal analysis and reporting, allows for dynamic mapping, graphing, and display of a wide variety of physical, hydrological, and geochemical data as stand alone charts or overlays to any georeferenced spatial data sets, such as topographic maps, aerial photographs, and CAD data. The system also allows for the storage and retrieval of sampling plans, field survey data, field and lab analysis, geochemical data analysis, satellite imagery, site images, drill logs and field logs (Fig.5). This system was used to optimize the creation of the backfill design plans, the stockpile sampling plans and the stockpile optimization plan by allowing both company and contract personnel working on the project to interact with a single set of data.

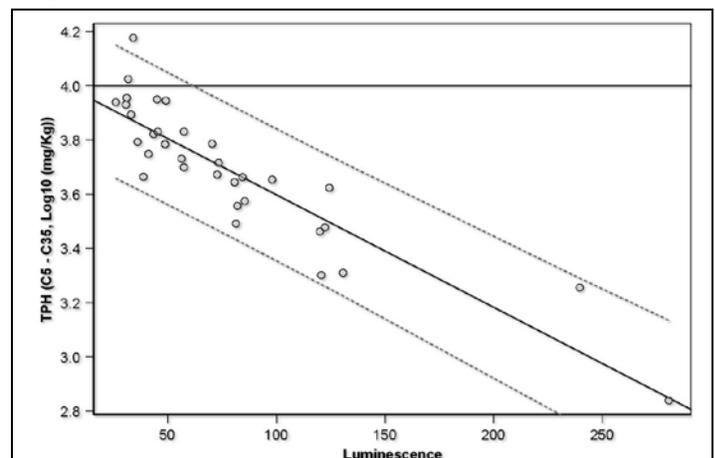


Fig. 4. Correlation between field luminescence data and laboratory TPH results with 95% prediction interval.

Stockpile dismantling is organized by using the quarter hectare (QH) grid designations defined for each of the five stockpiles. This allows for field notes to be taken during the work effort and associated with a given QH grid, thus documenting the TPH concentrations of material retrieved from each stockpile and its eventual disposition in the backfill area. Once a given QH grid has been tasked for use in the backfill effort, its corners are marked with flags or colored paint. After a grid has been characterized using the colorimeter, the entire grid can then be dismantled by removing material from the grid area and loading it into designated trucks. Trucks transport TPH concentration type-segregated material to the backfill area and place the material in the area designated for that particular material based on a colored flag system (e.g., green flags for Type A and orange flags for Type B material).

Access to robust data processing allowed the project to pursue a contracting strategy designed to reduce business risk and conserve resources. Before the backfill effort was initiated, a GPS survey was performed to establish the existing baseline elevations. Monthly GPS surveys are performed to capture the changes to the stockpile areas. These surveys are loaded into the GIS environment and used to generate the incremental volume change reports that are used in the invoicing process for the earth moving contractor. These monthly surveys are also used to provide feedback to the project team in the form of graphical and tabular reports showing incremental and overall backfilled material volumes and reduction of stockpiles.

## 5 OPTIMIZED PROJECT MANAGEMENT AND DESIGN

The implementation of the enhanced GIS/Document Management System has ensured the ability to keep all project associated data and files organized and available for retrieval at any time in the future. The modular design of the system allows for additional functionality to be added without degrading or impacting the existing modules. This system is also designed to support use of industry-standard formats (i.e. .shp, .dxf, .tif, .jpg). For example, GPS reference locations, photography and chemical data can all be archived within the same platform allowing cross-correlation between data entities and easy mapping of a variety of data elements (e.g., TPH concentration, topography, interim and final grades, etc.) throughout the course of the project.

Normal engineering projects typically work on a linear, phased approach (i.e. 30% design followed by 60%, and complete design, costing, contracting and build). In the Wafra case, a more dynamic approach was necessary to meet the exigencies of the schedule and to optimize contractor efficiencies. Therefore a Remedial Active Management Plan (RAMP) was developed which allowed for overlaps between designs such that pit excavation and removal activities would be undertaken in parallel with backfilling of Type B material and ongoing coverage with Type A material, all in different areas. This ap-

proach also accommodates future pilot testing of landfarming and re-vegetation techniques and has shortened the anticipated length of the project from five years to three years while saving on transaction costs.



Fig. 5. Integrated GPS/GIS georeferenced (topographic map, aerial photograph and satellite imagery) data management system used to optimize environmental engineering and remediation.

From a practical perspective the first phase of RAMP prepares a 30% design with the follow-on phases of design based on data collected/calculations made during the first phase. The final phase of work establishes the ultimate ground surface and incorporates earlier designs seamlessly into the interim as-built documentation. The accrued benefits are uninterrupted remediation with simple decisions made up front and limited opportunity for adverse effects, while time is available to make informed decisions on more complex issues as the process progresses.

## 6 CONCLUSION

The ultimate outcome of environmental stewardship at the Wafra facility will result in an environmentally robust desert revitalization program that converts 380 hectares of a produced water evaporation pond area into a thriving desert community, while safely and effectively managing over two million cubic meters of stockpiled oily sand. Risk-based clean-up goals, developed under USEPA methodology along with well established international standards, are the foundation which allowed implementation of novel decision making and sound remedial design. Further, utilization of GPS and GIS applications, and effective integration of sophisticated computer technology into overall project design optimized environmental engineering and remediation.

This innovative project can be used as a model for other oil field areas within Kuwait, Gulf Cooperation Council (GCC) states, and other parts of the world requiring crude oil impacted soil remediation and produced water pond closure.

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