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I. From the Editor

On behalf of The West Indian Journal of Engineering, I would like to update you some of its latest work in progress below:

Firstly, out of 26 manuscripts received and reviewed for the current Volume 35, Number 2, 14 papers were accepted for publications.

Secondly, we have extended the submission deadline of paper to next Special issue (with the theme on ‘Project Management/Engineering Initiatives and Challenges for a Sustainable World’) to 28th February 2013. We look forward to receiving more scholarly work and submissions. The review and editorial tasks for this issue have been commenced in line with meeting the tight schedule of targeted publication of this issue by July 2013.

Thirdly, our WIJE Website Project to digitise the journal’s paper archives had been progressing on schedule. It is anticipated that it would be complete within 2013. The web site address is http://sta.uwi.edu/eng/wije/

II. About This Volume

This Volume 35 Number 2 includes fourteen research articles. The relevance and usefulness of respective articles are summarised below.

J. Rajnauth and C. Boodoo, “Trinidad and Tobago’s First Deepwater Drilling Campaign”, look at the major problems, risks and uncertainties encountered during the drilling of the oil and gas wells offshore and highlight key lessons that would be useful for further drilling in the deep and ultra deep waters off Trinidad and Tobago. It examines the main objectives of well drilling.

J. Rajnauth, M. Barrufet, and G. Falcone, “Potential Industry Applications Using Gas Hydrate Technology”, propose a workflow for capturing, storing and transporting gas in the hydrate form, particularly for situations where there are infrastructural constraints such as lack of pipelines with reference to Trinidad and Tobago. These applications of gas hydrate technology can have potential benefits to the oil and gas industry.

R. Hosein, T. Jagai and R.A. Dawe, “A Method for Predicting the Phase Behaviour of Trinidad Gas Condensates”, evaluate the dew point pressure, gas compressibility factor (z factor), liquid volume and produced gas (Constant Volume Depletion, CVD data) and determine from a tuned Equation of State (EOS). The study tests the Peng-Robinson EOS and predicts CVD data for six Trinidad gas condensate samples using the compositional analysis with Single Carbon Number 24 (SCN24).

K.K. Alaneme, “Mechanical Behaviour of Cold Deformed and Solution Heat-treated Alumina Reinforced AA 6063 Metal Matrix Composites”, investigates into the mechanical behaviour of cold deformed and solution heat-treated aluminium alloy (6063). AA 6063-Al₂O₃ particulate composites having 6, 9, and 12 volume percent of Al₂O₃ were produced using two-step stir casting process. It was found that the tensile strength and yield strength increased with increase in alumina volume percent and degree of cold rolling.

E. Ali, E.I. Ekwu, J. Bridge and R. Birch, “A Three-Stack Mechanical Sieve Shaker for Determining Aggregate Size Distribution of Soils”, describe the design, construction and testing of a soil dry sieving apparatus with dry soil samples. Three stacks of sieves are incorporated into the design. This decreases by almost three times, the normal time required for aggregate size analysis using the existing commercial shakers, which all utilise single sieve stacks.

R. Akinoso and I.M. Lasisi, “Effect of Cooking Time on Select Physical and Mechanical Properties of Dried Pigeon pea (Cajanus cajan)”, investigate into the effect of cooking duration on select physical and mechanical properties of dried pigeon pea. Various cooking times at 100°C were used. Means of 250 replicates were calculated and data analysed using ANOVA and regression. The data generated can be used to improve the processing technology of pigeon pea.

R. Akinoso and N.E. El-alawa, “Some Engineering and Chemical Properties of Locust Bean (Parkia biglobosa)”, determine effect of cooking duration on some engineering and chemical properties of locust bean seed. Results showed that cooking duration influenced size, shape, and moisture absorption capacity of locust bean. Compressive strength and deformation of the crop were functions of the cooking duration. Effects of cooking on physical and mechanical properties of locust beans were not linear, thus an optimum cooking duration is required.

F.T. Fayose, “Expansion Characteristics of Selected Starchy Crops During Extrusion”, investigates the effect of extrusion process parameters of a locally developed extruder on the expansion of extrudates of the flour and starch of maize and cassava. Response Surface Methodology, stepwise regression, correlation and Analysis of Variance were employed to a factorial experiment in completely randomised design. Results showed that these starchy crops at low extrusion time are smooth and can be suitable for pasta products.

G.M. Mwangi and G.B. Oguntimein, “Design of an Activated Carbon System for the Treatment of Fermentation Wastewater from a Bioethanol Production Process”, determine the adsorption capacity of activated carbon to remove the dissolved organics using fermentation wastewater from bioethanol process containing salts. The study measured the performance of activated carbon system for the treatment of wastewater from a bioethanol process. Based on this study, a contacting system with multiple contacting beds in series is recommended.
J.J. Judicello et al., “Identification and Remediation of Water-Quality Hotspots in Havana, Cuba: Accounting forLimited Data and High Uncertainty”, developed a water-quality model to link in-stream concentrations with land uses in the Almendares River watershed, Cuba. A GIS platform was used to delineate the watershed and sub-watersheds and breakdown the watershed into urban and non-urban land uses.

S. Lowe, “An Epoch-based Metallogenic Scheme for Northern Guyana: A Tool for Mineral Resource Assessment”, reviews existing metallogenic schemes to assess their reliability as a tool for mineral resource assessment. A new scheme or conceptual model that uses metallogenic epochs as its building blocks is then proposed for and applied in northern Guyana.

A.A. Baboolal et al., “Petrophysical and Microhardness Characterization of the Sans Souci Formation, Trinidad”, attempt to revolve around mineralogical, topographical, elemental and microhardness distribution characteristics using various laboratory analysis techniques, including x-ray diffraction (XRD), scanning electron microscopy, physical properties characterisation and vickers hardness methods. The results would contribute to existing knowledge with respect to the petrophysical and microhardness characterisation of the Sans Souci Formation.

F. Muddeen and B. Copeland, “Microphone Placement for Tenor Pan Sound Recording: New Recommendations Based on Recent Research”, discuss the placement of recording microphones used for live recording, studio recording or sound reinforcement of a tenor steelpan. The study analyses the existing microphone techniques and the recommendations for new positions using the Nearfield Acoustical Holography (NAH) technique.

M.Y.R. Yiu, C.K. Sankat and K.F. Pun, “In Search of the Knowledge Management Practices in Organisations: A Review”, explore the multi-disciplinary nature of KM and discuss the components of the KM process in organisational settings. Several dominant KM approaches, and selected frameworks and models in industrial application domains are also discussed along with the need for future research on investigating the KM competence at both firm’s and industry’s levels.

III. Acknowledgements

On behalf of the Editorial Office, we gratefully acknowledge all authors who have made this special issue possible with their research work. We greatly appreciate the voluntary contributions and unfailing support that our reviewers give to the Journal.

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KIT FAI PUN, Editor-in-Chief
Faculty of Engineering,
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January 2013
Trinidad and Tobago’s First Deepwater Drilling Campaign

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Abstract: Trinidad and Tobago is endowed with abundant oil and gas reserves both onshore and offshore. Most of the reserves offshore have been found in the shallow water shelf area. Over the last decade exploring the deep waters beyond the shelf (>1,000 meters) has been looked at with much anticipation. However, the eight (8) wells drilled thus far have not found hydrocarbons in commercial quantities. It is important to note however, that many geo-scientists believe the exploration work in the deepwater proved the existence of a working hydrocarbon system. The drilling phase of the exploration activities in the deepwater blocks (i.e. Blocks 25a, 25b, 26 and 27) produced many challenges. This paper looks at the major problems, risks and uncertainties encountered during the drilling of these wells and highlights key lessons that would be useful for further drilling in the deep and ultra deep waters off Trinidad and Tobago. The main objectives of well drilling would be examined. Results showed that some of the wells were unable to reach their technical objectives. As a result, the actual number of days and cost for some wells were less than that originally planned.

Keywords: Deepwater, Drilling, Trinidad and Tobago

Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbls</td>
<td>Barrels</td>
</tr>
<tr>
<td>BOP</td>
<td>Blow out Preventer</td>
</tr>
<tr>
<td>DHI</td>
<td>Direct Hydrocarbon Indicator</td>
</tr>
<tr>
<td>EMW</td>
<td>Effective Mud Weight</td>
</tr>
<tr>
<td>Ft</td>
<td>Feet</td>
</tr>
<tr>
<td>HC</td>
<td>Hydrocarbon</td>
</tr>
<tr>
<td>LOT</td>
<td>Leak off Test</td>
</tr>
<tr>
<td>LNG</td>
<td>Liquefied Natural Gas</td>
</tr>
<tr>
<td>LWD</td>
<td>Logging While Drilling</td>
</tr>
<tr>
<td>MDT</td>
<td>Modular Drill Stem Test</td>
</tr>
<tr>
<td>MWD</td>
<td>Measurement While Drilling</td>
</tr>
<tr>
<td>ppg</td>
<td>Pounds per gallon</td>
</tr>
<tr>
<td>psi</td>
<td>Pounds per square inch</td>
</tr>
<tr>
<td>PSC</td>
<td>Production Sharing Contract</td>
</tr>
<tr>
<td>RIH</td>
<td>Run in Hole</td>
</tr>
<tr>
<td>ROV</td>
<td>Remote Operated Vehicle</td>
</tr>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>TD</td>
<td>Total Depth</td>
</tr>
</tbody>
</table>

1. Introduction

In Trinidad and Tobago (T&T), the petroleum industry is one of the oldest in the hemisphere and historically, energy has been important to our economy. The first successful onshore well was drilled in 1866, and the first export of oil from Brighton took place in 1910. Not until 1968 though was commercial oil discovered off the east coast. This was followed by the discovery of gas off the north coast in 1971. In the 1990’s, significant gas had been discovered in the east coast marine area. This coupled with the establishment of several natural gas-based petrochemical plants and LNG plants prompted the search for more hydrocarbons in the deeper waters. This paper looks at the major problems, risks and uncertainties encountered during the drilling of wells, and discuss the lessons learnt for drilling in the deep and ultra deep waters off Trinidad and Tobago.

2. Reserves and Production Sharing Contracts

The oil and gas fields in T&T are depicted on the map in Figure 1. The solid areas indicate the oil fields while the shaded areas show the gas fields. The remaining proved and unproved reserves stand at about 570 million barrels of oil (National Energy Policy Consultations, 2010) and about 27 trillion cubic feet of gas (MEEA, 2010). Most of the hydrocarbon bearing acreage on the east coast of Trinidad is under Exploration and Production licensed agreements. Operations in the west coast area and on land are presently conducted by the state-owned company. Production sharing contracts (PSCs) were reintroduced in 1998, as T&T move into the deep-water exploration campaign.

The government of Trinidad and Tobago uses PSCs as vehicles to achieve a comprehensive exploration programme (Jupiter, 1998). This programme must be completed within a specified time frame that will optimise benefits derived by the state from any discovery being made. Natural gas is making an increasing contribution to the national economy with continuous further expansion anticipated.
Figure 2. Oil and Gas Fields in Trinidad and Tobago

As a result, it is imperative that natural gas exploration, development and commercialisation be effectively managed. Under the E&P licenses and the original PSC in 1974, no clear provisions were made for natural gas. The PSC contracts of 1996-1998 contain clauses that specifically address the development of natural gas, if such was found in the deepwater exploration campaign.

3. Deepwater Blocks
The blocks awarded in February 1998 were 25a, 25b, 26 and 27 (see Figure 2). These blocks are in the deepwater acreage, and the contracts involved:
- A five-year exploration phase of work programmes,
- Exploration wells to minimum commitment depths,
- Acquisition and processing of seismic data, and
- Attaining signature bonuses.

There are several objectives of the drilling campaign. These are summarised below:
1) To determine the presence of reservoir quality sands in the deep-water blocks.
2) To determine the hydrocarbon content of the primary and secondary objectives in the area.
3) To evaluate the pore pressure environment in the acreage and compare with predicted pressures.
4) To test the hydrocarbon potential of trapping configurations within the province of Trinidad deep water.
5) To gather valuable proprietary information in view of forthcoming and ultra deep water bid rounds (such as mud logging, Logging while drilling (LWD), wireline, pressure gradients, and fluid samples.)
6) To determine the presence of economic accumulations of hydrocarbons.
7) To prove that hydrocarbon charge has taken place in the deep water Columbus basin.
8) To drill the wells safely and within time and budget targets, and
9) To provide calibration of seismic data set and geological model for deep water.

4. Pre-drill Challenges
The deepwater sea floor is typical of mud volcanoes and seeps. Mud volcanoes are frequently conical and high relief in nature and can range from 165 ft to 7,500 ft in diameter and height from 130 ft to 400 ft (Leonard, 2000). Seeps are common on the seafloor and are fluid migration pathways that increase the risk of shallow water flows in the deepwater operations. There is also the possibility of gas hydrates in the shallow sediments (McCannell, 2001).
Deepwater geohazard surveys indicate the following shallow hazard assessment.

1) There are high risks associated with shallow water flows.
2) Localised shallow hydrocarbon reservoirs may be present in the upper 2,800 ft of sediments.
3) Very high currents were expected along channel margins. The high currents arise from eddies which break off from the main North Brazil Current (NBC). These currents can increase riser ball joint angles and riser tensions to above normal operational limits.
4) The possibility of over pressure in the subsurface due to fluid expulsion features. Active mud flows can put unacceptable lateral load on structural casing. Given their size and relief, side slopes may be unstable and should be considered when designing mooring pattern or picking a surface location. Hard ground, present near mud volcanoes and active sea floor vents, may impact anchor placement, deployment and tensioning.
5) There are high variable surficial and near surface sediments with variable shear strength values that could impact structural casing design and emplacement methods as well as anchor holding capacity.
6) There are easily identifiable surface faults, and
7) Submarine channels with steep and unstable margins may be present and serve as conduits for turbidity flows.

Good well planning would be key to the success of reaching the objectives. Some wells were planned attempting to address as many of the geohazard problems as possible. Mitigations for the deep-water regional geohazards and uncertainties are considered. A pilot hole could be drilled to assist with uncertainty in the shallow region. The pilot hole could help 1) identify shallow water flow in the vicinity of the well location, 2) establish hole conditions (pore pressure/hole stability) until the 20” casing depth and beyond if possible, 3) attain a 20” casing setting depth with an objective to optimise casing programme, and 4) optimise jetting programme (with 36” structural pile length and jetting parameters).

Besides, the selection of fit for purpose deepwater drilling rigs which are especially capable of handling high currents and good positioning capabilities is important. There are currents derived from the North Brazil Current that flows northwest along the coast of South America and turns north to offshore Trinidad. Offshore operations can therefore be affected by the types and scales of current, from short-lived high-frequency variations that last just minutes to longer time-scale and more predictable features (such as tidal currents).
5. Deepwater Drilling and Problems Encountered

Table 1 shows a summary of the eight wells drilled in the deepwater acreage. The summary highlights the actual number of days on each well, actual drilled depth and actual cost of well compared to what was planned. It can be seen that none of the wells reached its planned total depth. There are several reasons for aborting drilling operations for these wells (see Table 2). The rig types used were semi submersible dynamic position for three wells and drill ships for five wells. These rigs were supposed to have high current handling capabilities. The table also gives the period during the year the wells were drilled. Seven of the wells were drilled between the October-March period while the other well between the April-June period.

Even though adequate planning went into the drilling of these wells, some major problems associated with deepwater operations were encountered. These include situations arising out of currents, shallow hazards and well problems (see Table 3).

Table 1. A Summary of Wells Drilled in Deepwater Acreage

<table>
<thead>
<tr>
<th>Well Name</th>
<th>Well 1</th>
<th>Well 2</th>
<th>Well 3</th>
<th>Well 4</th>
<th>Well 5</th>
<th>Well 6</th>
<th>Well 7</th>
<th>Well 8</th>
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<tr>
<td>Block</td>
<td>25 a</td>
<td>25 a</td>
<td>25 a</td>
<td>25 b</td>
<td>26</td>
<td>25 b</td>
<td>26</td>
<td>27</td>
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<tr>
<td>Water Depth (ft)</td>
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<td>3500</td>
<td>4400</td>
<td>3400</td>
<td>3000</td>
<td>3800</td>
<td>4400</td>
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<tr>
<td>Spud Date</td>
<td>1/10/99</td>
<td>13/1/03</td>
<td>29/1/03</td>
<td>6/12/00</td>
<td>10/2/01</td>
<td>4/3/02</td>
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<tr>
<td>AFE days</td>
<td>38.3</td>
<td>21</td>
<td>17.9</td>
<td>76</td>
<td>80</td>
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<td>Actual days</td>
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<td>19</td>
<td>15</td>
<td>68</td>
<td>94</td>
<td>31.2</td>
<td>27.6</td>
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<tr>
<td>Planned TD (ft)</td>
<td>11500</td>
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<td>Actual TD (ft)</td>
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<td>16300</td>
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<tr>
<td>AFE Cost (MMUSD)</td>
<td>21</td>
<td>8.48</td>
<td>9.33</td>
<td>34</td>
<td>42</td>
<td>34</td>
<td>31.3</td>
<td>59</td>
</tr>
<tr>
<td>Actual Cost (MMUSD)</td>
<td>18.1</td>
<td>7.44</td>
<td>7.93</td>
<td>24.8</td>
<td>35</td>
<td>16.4</td>
<td>34.8</td>
<td>76</td>
</tr>
<tr>
<td>Rig Type</td>
<td>Semi-sub</td>
<td>Semi-sub</td>
<td>Semi-sub</td>
<td>Drill Ship</td>
<td>Drill Ship</td>
<td>Drill Ship</td>
<td>Drill Ship</td>
<td>Drill Ship</td>
</tr>
</tbody>
</table>

Table 2. Reasons for Aborting Well Drilling Operations

<table>
<thead>
<tr>
<th>Well # / Block</th>
<th>LTI</th>
<th>EI</th>
<th>Primary Objective</th>
<th>Secondary Objective</th>
<th>Planned TD Achieved</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (25a)</td>
<td>X</td>
<td>X</td>
<td>YES</td>
<td>YES</td>
<td>X</td>
<td>Increased Pore Pressure. Lack of prospective lower horizons. Well abandoned.</td>
</tr>
<tr>
<td>2 (25a)</td>
<td>X</td>
<td>X</td>
<td>YES</td>
<td>YES</td>
<td>X</td>
<td>Deteriorating hole conditions. Abandoned dry hole with gas and condensate shows.</td>
</tr>
<tr>
<td>3 (25a)</td>
<td>X</td>
<td>X</td>
<td>YES</td>
<td>NO</td>
<td>X</td>
<td>Abandoned due to mechanical problems.</td>
</tr>
<tr>
<td>4 (25b)</td>
<td>X</td>
<td>Y</td>
<td>YES</td>
<td>YES</td>
<td>X</td>
<td>Pore pressure and fracture gradients were lower than expected. Abandoned due to hole instability.</td>
</tr>
<tr>
<td>5 (26)</td>
<td>X</td>
<td>X</td>
<td>YES</td>
<td>YES</td>
<td>X</td>
<td>Atlantic eddy currents impacted on operations. Pore pressure and fracture gradients lower than expected. Well abandoned due to well control event.</td>
</tr>
<tr>
<td>6 (25b)</td>
<td>Y</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>X</td>
<td>Atlantic eddy currents impacted operations. Pore pressure and fracture gradients were lower than predicted. Lack of prospective lower horizons. Well abandoned dry hole.</td>
</tr>
<tr>
<td>7 (26)</td>
<td>X</td>
<td>X</td>
<td>YES</td>
<td>YES</td>
<td>X</td>
<td>Pore pressure and fracture gradients were lower than predicted. Slightly over budget. Lack of prospective lower horizons. Well abandoned dry hole.</td>
</tr>
<tr>
<td>8 (27)</td>
<td>X</td>
<td>X</td>
<td>YES</td>
<td>YES</td>
<td>X</td>
<td>Atlantic currents impacted operations. Pore pressure and fracture gradients lower than predicted. Exceeded budget and time allocations due to hole problems and sidetracking of well three times. Well control problems. Well abandoned dry hole.</td>
</tr>
</tbody>
</table>

*Keys: LTI - Lost Time Incidents; EI - Environmental Incidents; X - No*

Table 3. Well Problems Associated with Deepwater Operations

<table>
<thead>
<tr>
<th>Well# / (Block)</th>
<th>Currents</th>
<th>Shallow Hazards</th>
<th>Well problems /Pore Pressure</th>
<th>Pilot Hole</th>
<th>Non Productive time %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (25a)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>10</td>
</tr>
<tr>
<td>2 (25a)</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>3 (25a)</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>4 (25b)</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>16</td>
</tr>
<tr>
<td>5 (26)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>18.2</td>
</tr>
<tr>
<td>6 (25b)</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>22.4</td>
</tr>
<tr>
<td>7 (26)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>5.7</td>
</tr>
<tr>
<td>8 (27)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>37</td>
</tr>
</tbody>
</table>
5.1 Problems with Currents

Atlantic Eddy currents had significant impact on Well 5 operations; there were four (4) attempts at running the riser with a resulting downtime of 15.2 days. It took about one week to run the Blow out Preventer (BOP) and riser on Well 8. The drill ship actually went south in order to avoid the strong currents. The highest recorded current during operations on Well 1 was 3.3 knots, which occurred while running wireline logs. However, the rig was able to maintain its position on location.

5.2 Shallow Hazards and Well Problems

**Well 1**

Well 1 encountered shallow gas which was regarded as minor and slightly overpressure with just a stream of bubbles observed at the wellhead. The flow was observed while drilling the pilot hole. The well was controlled with eleven pounds per gallon (11 ppg) mud and flow checked before continuing operations. While running the BOP on riser during Well 5 operations, a flow was observed at the sea floor. This gradually increased and plummed up to forty-eight feet (48 ft) in height (see Figure 3). A pilot hole was then drilled to five thousand two hundred feet (5,200 ft) and traces of bubbles were seen. The shallow water flow subsided with time. During the Well 3 operations, the 12 ¼” hole was drilled trouble free to a depth of 8,078 ft, when the cameras on the Remote Operated Vehicle (ROV) underwater showed a plume of gases around the BOP stack caused by a buildup of hydrates.

![Figure 3. Shallow Water Flow Block 26 Deepwater Trinidad](image)

**Well 2**

Due to limited drilling margin, the 9 5/8” casing was set early at 7,511 ft. While drilling the 8 ½” hole section, indications of increasing formation pressure again suggested there was inadequate drilling margin to proceed. The well was then reached the total depth (TD) at 8,787 ft.

**Well 3**

The BOP stack appeared to be leaning at 3-4 degrees at the end of drilling the 12 ¼” hole section (8,074 ft). After performing a flow check and preparing to pull out of the hole, it was observed that there was excessive drag on the assembly and the rate of pull was extremely slow. In attempting to establish circulation that assists in pulling the drill string out of the hole, circulation and rotation were found to be near impossible. The string was held up above the drill collars. The decision was then made to TD of the well at this point.

**Well 4**

A pore pressure ramp up was expected below the 9 5/8” casing depth and therefore the plan was to drill the 8 1/2” hole as deep as possible and use a 7 5/8” liner to enable drilling a 6 ½” hole to the commitment depth. After setting 7 5/8” liner, the mud weight was increased to 13.5 ppg where a 15.2 ppg leak off test (LOT) was obtained. While cleaning out the 8 ½” rat hole beneath the liner, the hole began packing off and after several days it was impossible to keep the hole open long enough to drill deeper than 12,017 ft. As a result, there was no choice but to reach the TD of the well at this point.

**Well 5**

Well 5 experienced an increase in pore pressures as indicated by rising connection gas. The well was stopped to circulate and the mud weight was increased to 15.3 ppg. With the increased mud weight, the well began losing returns at a rate of 120 bbls/hr. Calculations indicated that the Effective Mud Weight (EMW) at the 7 5/8” liner shoe was just under the LOT results, providing no kick tolerance. The well reached its TD of 14,085 ft.

**Well 6**

Three riser tensioner lines broke and all were replaced which led to a one week down time.

**Well 7**

Well 7 had no shallow hazards issues or major drilling problems. The well reached its TD of 12,027 ft. due to a lack of prospective horizons below this depth.

**Well 8**

The 8 ½” drilling assembly was RIH and cement was tagged at 15,042 ft. The cement was drilled out, together with float collar and 9 5/8” shoe at 15,179 ft. While drilling through new formation, the pump pressure increased from 3,000 psi to 4,000 psi. There were also losses of 25 barrels in the active system following which the hole packed off. The flow rate was reduced and then slowly increased to full circulation. Ten feet of new formation was then drilled to 15,552 ft and a LOT of 15.3 ppg was obtained. The hole was drilled ahead to 16,751 ft. A drop in pump pressure was observed with erratic torque and the well began to flow (i.e., a 7 bbls salt water kick). The well was killed with 18 ppg heavy
pill on bottom, after 14.2, 14.4 and 14.8 ppg mud weights were unsuccessful. The well had to be TD’ed at this point as mud weights and LOT were 0.5 ppg apart and the well could not be controlled.

Figure 4 shows a typical deepwater casing programme schematic. Casing liners are used as casing contingencies in cases where it may be impossible to reach the proposed casing setting depth. These casing contingencies allow the operator to drill as deep as possible with the aim of reaching the total depth. The two casing liners were used in the drilling operations. These were the 16” and 11 ¾” liner casings. In some cases, a 7 5/8” liner can also be used to enable drilling a 6 ½” hole as in the case of drilling Well 4.

Some wells (1, 5 and 8) utilised drilling pilot holes (see Table 3). In fact, Well 5 encountered shallow gas flow problems and then it was decided to drill a pilot hole. Well 3 did not utilise drilling a pilot hole but encountered shallow water flows. Non Production Time (NPT) as a percentage of total well time is also highlighted. Information for some wells was not obtained. Some wells showed significant NPT ranging from 16 % to 22%. These include problems associated with BOPs, casing, top drive, weather, shallow water flows and other rig equipment.

Though the problems encountered provided great challenges, the primary objectives of all the wells were penetrated and the data collected can provide a better understanding of the deepwater blocks (see Table 2). Since most of the wells did not reach their total depth, the success of drilling was evaluated looking at days and cost to drill 1,000 ft. Figure 5 shows the proposed and actual days to drill 1,000 ft, and that 50% of the wells were within the proposed days to drill. Figure 6 gives a snapshot of the proposed and actual cost to drill 1,000 ft. It can be seen that 5 of the 8 wells were drilled within budget, and all eight wells were drilled without a lost time incident.

6. Exploration Lessons
This drilling phase gave a better understanding of the blocks in terms of traps, seals, reservoir, source adequacy and geophysical model. Table 4 shows some of the exploration learning for each block and Table 5 gives hydrocarbon indication, reservoir description and data collection for each well.

Thermogenic gas was seen in Blocks 25a and 26. This is likely an indication that there is a migration pathway in the prospect area. Low gas saturation wet sands were seen in Block 25b and this corresponds to seismic reflectors. It is likely therefore that low gas saturated wet sands and hydrocarbon bearing sands showed similar seismic responses. Blocks 25a, 26 and 27 all give positive indication of traps. There still remain questions on the hydrocarbon system viability. Pore pressure prediction was reasonably accurate compared to
pre-drill prediction from seismic. The Block 27 well did not achieve the objectives stated in the well’s proposal, i.e. drill 300 ft below the reflector event at the base of the TP 25 interval. The logs, cores, check shot surveys and fluid samples data can be used to calibrate the seismic data set and geological model for the blocks.

### 6.1 Comparison of Actual and Prognosed Depth of Formation Tops

Table 4. A Summary of Exploration Lessons

<table>
<thead>
<tr>
<th>Block</th>
<th>Trap/Seal</th>
<th>Reservoir</th>
<th>Source Adequacy</th>
<th>Geophysical Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 a</td>
<td>The presence of traps, including trapped hydrocarbons in the block</td>
<td>The presence of significant reservoir quality sands in deep-water block 25a confirmed. Some of the objectives had poor reservoir development. Thermogenic hydrocarbons were seen, however the volumes were small</td>
<td>The key questions still remain on hydrocarbon system viability</td>
<td>The rock properties in penetrated intervals were determined. Pore pressure predictions reasonably accurate.</td>
</tr>
<tr>
<td>25 b</td>
<td>The riskiness of stratigraphic traps was confirmed; likely reason for failure in the block</td>
<td>The presence of significant reservoir quality sands in deep-water block 25b confirmed. There were more sand in secondary objective than anticipated</td>
<td>The key questions still remain on hydrocarbon system viability</td>
<td>The rock properties in penetrated intervals were determined. Pore pressure predictions were reasonably accurate</td>
</tr>
<tr>
<td>26</td>
<td>The large structural closure was present with adequate seal confirmed by hydrocarbon presence</td>
<td>The Pliocene primary objectives lack significant sand. However, sand presence was confirmed in Pleistocene secondary objectives</td>
<td>The presence of thermogenic gas indicates that there is a viable migration pathway in prospect area (most likely deep-cutting faults). Despite adequate migration pathway, no oil was observed</td>
<td>The rock properties in the penetrated intervals were determined. Pore pressure predictions were reasonably accurate</td>
</tr>
<tr>
<td>27</td>
<td>The presence of several different pressure compartments indicate the presence of intraformational seals within the mid to Lower Pliocene</td>
<td>Primary objective were composed of claystones interbedded with thin sandstones while the secondary target interval consisted of claystones with interbedded massive sands</td>
<td>Given that a thermogenic component appears to be absent, the understanding of migration rates and actual mechanism needs to be further reviewed</td>
<td>The rock properties in penetrated intervals were determined</td>
</tr>
</tbody>
</table>

Table 5. Reservoir Description and Hydrocarbon Indication for Each Well

<table>
<thead>
<tr>
<th>Well # / Block</th>
<th>Hydrocarbon indication</th>
<th>Reservoir Description</th>
<th>Data Collection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (25a)</td>
<td>Biogenic and Thermogenic gas</td>
<td>The objective section encountered poorly developed gas bearing sands. Better developed sand were encountered but were all wet.</td>
<td>Gamma, Ray, Resistivity, Density Neutron, Sonic, PWD, Mud Logging</td>
</tr>
<tr>
<td>2 (25a)</td>
<td>Biogenic and Thermogenic gas</td>
<td>The target section was dominated by silstone, sandstone and claystones.</td>
<td>Gamma, Ray, Resistivity, Density Neutron, PWD, Mud Logging</td>
</tr>
<tr>
<td>3 (25a)</td>
<td>Wet Sands</td>
<td>The well encountered well developed with good reservoir properties</td>
<td>Gamma, Ray, Resistivity, Density Neutron, PWD, Sidewall cores, Check Shot Survey, MDT, Mud Logging</td>
</tr>
<tr>
<td>4 (25b)</td>
<td>Wet Sands. Thin section with biogenic gas</td>
<td>The primary target consisted of a series of well developed from 5 ft to 93 ft thick with good reservoir properties.</td>
<td>Gamma, Ray, Resistivity, Density Neutron, PWD, Sidewall cores</td>
</tr>
<tr>
<td>5 (26)</td>
<td>30’ section of biogenic gas. Thermogenic gas also seen.</td>
<td>The sands were poorly developed in the primary objective while thin channel sand were encountered in secondary target</td>
<td>Gamma, Ray, Resistivity, Density Neutron, PWD, Sidewall cores, Check Shot Survey, MDT, Mud Logging</td>
</tr>
<tr>
<td>6 (25b)</td>
<td>Water wet sands. Small gas peaks of biogenic gas.</td>
<td>The primary objective section comprised mainly of claystone with a series of thin sands and two thick well developed sand bodies.</td>
<td>Gamma, Ray, Resistivity, Density Neutron, PWD, Mud Logging</td>
</tr>
<tr>
<td>7 (26)</td>
<td>Wet sands</td>
<td>The sands were well developed often up to 50 ft in thickness</td>
<td>Gamma, Ray, Resistivity, Density Neutron, PWD, Mud Logging</td>
</tr>
<tr>
<td>8 (27)</td>
<td>Several thin packages of biogenic gas</td>
<td>Significant sand development was encountered in the secondary target, with several thin sands in the primary target interval</td>
<td>Gamma, Ray, Resistivity, Density Neutron, PWD, MDT, Mud Logging</td>
</tr>
</tbody>
</table>
### Table 6. Comparison of Actual versus Prognosed Depth for Formation Tops

#### Block 25 a (Well 1)

<table>
<thead>
<tr>
<th>Tops</th>
<th>Prognosed Depth, ft</th>
<th>Actual Depth, ft</th>
<th>Difference, ft</th>
<th>Difference, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3996</td>
<td>3963</td>
<td>33</td>
<td>0.83</td>
</tr>
<tr>
<td>10</td>
<td>4416</td>
<td>4374</td>
<td>42</td>
<td>0.95</td>
</tr>
<tr>
<td>15</td>
<td>5446</td>
<td>5387</td>
<td>59</td>
<td>1.09</td>
</tr>
<tr>
<td>20</td>
<td>6011</td>
<td>5919</td>
<td>92</td>
<td>1.53</td>
</tr>
<tr>
<td>30</td>
<td>6706</td>
<td>6552</td>
<td>154</td>
<td>2.30</td>
</tr>
<tr>
<td>35</td>
<td>6985</td>
<td>6811</td>
<td>174</td>
<td>2.50</td>
</tr>
<tr>
<td>40</td>
<td>7608</td>
<td>7303</td>
<td>305</td>
<td>4.00</td>
</tr>
<tr>
<td>45</td>
<td>7930</td>
<td>7666</td>
<td>264</td>
<td>3.30</td>
</tr>
<tr>
<td>50</td>
<td>8360</td>
<td>8068</td>
<td>292</td>
<td>3.50</td>
</tr>
<tr>
<td>55</td>
<td>8757</td>
<td>8409</td>
<td>308</td>
<td>3.50</td>
</tr>
<tr>
<td>55 sand top</td>
<td>8818</td>
<td>8550</td>
<td>328</td>
<td>3.72</td>
</tr>
</tbody>
</table>

#### Block 25 a (Well 2)

<table>
<thead>
<tr>
<th>Tops</th>
<th>Prognosed Depth, ft</th>
<th>Actual Depth, ft</th>
<th>Difference, ft</th>
<th>Difference, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>12(Primary)</td>
<td>7576</td>
<td>7462</td>
<td>114</td>
<td>1.5</td>
</tr>
<tr>
<td>11.8</td>
<td>8531</td>
<td>8298</td>
<td>233</td>
<td>2.70</td>
</tr>
<tr>
<td>11.7</td>
<td>8938</td>
<td>8921</td>
<td>17</td>
<td>0.18</td>
</tr>
<tr>
<td>11</td>
<td>9738</td>
<td>Did not penetrate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Block 25 a (Well 3)

<table>
<thead>
<tr>
<th>Tops</th>
<th>Prognosed Depth, ft</th>
<th>Actual Depth, ft</th>
<th>Difference, ft</th>
<th>Difference, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 55</td>
<td>6481.5</td>
<td>6890</td>
<td>44</td>
<td>0.70</td>
</tr>
<tr>
<td>Level 70</td>
<td>7907</td>
<td>7874</td>
<td>33</td>
<td>0.42</td>
</tr>
<tr>
<td>Level 75</td>
<td>9016</td>
<td>Did not penetrate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 90</td>
<td>10056</td>
<td>Did not penetrate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Block 25 b (Well 4)

<table>
<thead>
<tr>
<th>Tops</th>
<th>Prognosed Depth, ft</th>
<th>Actual Depth, ft</th>
<th>Difference, ft</th>
<th>Difference, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>P82</td>
<td>7363</td>
<td>7585</td>
<td>222</td>
<td>2.90</td>
</tr>
<tr>
<td>P105</td>
<td>8937</td>
<td>8955</td>
<td>18</td>
<td>0.20</td>
</tr>
<tr>
<td>P110</td>
<td>9515</td>
<td>9510</td>
<td>5</td>
<td>0.05</td>
</tr>
<tr>
<td>P115</td>
<td>9741</td>
<td>9790</td>
<td>49</td>
<td>0.50</td>
</tr>
<tr>
<td>P121</td>
<td>10027</td>
<td>10010</td>
<td>17</td>
<td>0.17</td>
</tr>
<tr>
<td>P150</td>
<td>10781</td>
<td>10790</td>
<td>9</td>
<td>0.08</td>
</tr>
<tr>
<td>P165</td>
<td>11628</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Block 26 (Well 5)

<table>
<thead>
<tr>
<th>Tops</th>
<th>Prognosed Depth, ft</th>
<th>Actual Depth, ft</th>
<th>Difference, ft</th>
<th>Difference, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>P120</td>
<td>7582</td>
<td>7642</td>
<td>60</td>
<td>0.80</td>
</tr>
<tr>
<td>P150</td>
<td>11940</td>
<td>11877</td>
<td>63</td>
<td>0.53</td>
</tr>
<tr>
<td>P190</td>
<td>13240</td>
<td>13240</td>
<td>156</td>
<td>1.16</td>
</tr>
</tbody>
</table>

#### Block 25 b (Well 6)

<table>
<thead>
<tr>
<th>Tops</th>
<th>Prognosed Depth, ft</th>
<th>Actual Depth, ft</th>
<th>Difference, ft</th>
<th>Difference, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>P80 (Secondary)</td>
<td>6758</td>
<td>6675</td>
<td>7</td>
<td>0.10</td>
</tr>
<tr>
<td>P100(Secondary)</td>
<td>7282</td>
<td>7325</td>
<td>43</td>
<td>0.60</td>
</tr>
<tr>
<td>P150(Primary)</td>
<td>10914</td>
<td>10890</td>
<td>24</td>
<td>1.10</td>
</tr>
</tbody>
</table>

#### Block 26 (Well 7)

<table>
<thead>
<tr>
<th>Tops</th>
<th>Prognosed Depth, ft</th>
<th>Actual Depth, ft</th>
<th>Difference, ft</th>
<th>Difference, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>P133(Primary)</td>
<td>9575</td>
<td>9507</td>
<td>68</td>
<td>0.71</td>
</tr>
<tr>
<td>P150(Secondary)</td>
<td>10251</td>
<td>10200</td>
<td>51</td>
<td>0.50</td>
</tr>
</tbody>
</table>

#### Block 27 (Well 8)

<table>
<thead>
<tr>
<th>Tops</th>
<th>Prognosed Depth, ft</th>
<th>Actual Depth, ft</th>
<th>Difference, ft</th>
<th>Difference, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP 50 (Secondary)</td>
<td>12185</td>
<td>11661</td>
<td>524</td>
<td>4.30</td>
</tr>
<tr>
<td>TP 35 (Primary)</td>
<td>13819</td>
<td>12998</td>
<td>764</td>
<td>5.50</td>
</tr>
<tr>
<td>TP 25 (Primary)</td>
<td>15354</td>
<td>14116</td>
<td>1238</td>
<td>7.60</td>
</tr>
<tr>
<td>TP 25 base (Primary)</td>
<td>16164</td>
<td>Not Penetrated</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.2 Exploration Implications

**Block 25a**
1) The lack of proven hydrocarbon in reservoirs increases the concern of the potential of the block.
2) The presence of thermogenic gas (up to C5 in some cases) indicates there is a viable migration pathway in the block.

**Block 25b**
1) The chance of success of other stratigraphic trap prospects is lower than originally assessed due to inability to distinguish low saturation gas from other hydrocarbon scenarios.
2) The lack of any thermogenic hydrocarbon indicators (shows other than C1) suggests hydrocarbon charge to subsurface reservoirs remains unproven from the tertiary source interval.
3) The block’s seismic dataset can be confidently used for lithology prediction.

**Block 26**
1) The block’s seismic dataset can be confidently used for lithology prediction.
2) The lack of sand in some of the primary objectives significantly increases reservoir risk for deeper intervals on the blocks.
3) The presence of small amounts of thermogenic gas indicates there is a migration pathway in the block.
4) Well 5 would be important in calibrating seismic response to potential reservoir sands in deeper intervals since Vertical Seismic Profile (VSP) data and core data were obtained.

**Block 27**
1) The well’s inability to prove up a working petroleum system has increased the charge risk on Block 27 prospects.
2) According to the well’s objective statement, to be considered a good exploration test, the well should have tested the entire primary target interval (TP35 to base TP 25), hence validating the model for significant reservoir presence in the lower Pliocene. This well did not achieve the objectives stated, i.e. drill 300 ft below the reflector event at the base of the TP 25 interval to be considered a good exploration test. The well did not completely penetrate the TP25 seismic target hence it cannot be considered an effective test. The well penetrated the top of the TP25 primary target and drilled 30 feet of sands that were partially logged by the gamma ray tool and described by the well site loggers. No wireline or VSP data was collected and the absence of a caliper log hindered detailed petrophysical evaluation whilst establishing a proper tie to the seismic data was not a straightforward process.
3) Reservoir continuity and thickness was a significant prospect risk because the quality of imaging did not allow for proper segment definition.
4) Post drill analysis can involve calibration of the seismic reflectivity to sands; hence some reduction in uncertainty but segment definition remains difficult.
5) The trap, a large four-way closure, is fairly robust and was not assigned a high risk. Modular Drill Stem Test (MDT) pressures confirm the presence of intra formational seals in the mid to lower Pliocene section, indicating the mudstones associated with condensed sections can be effective seals.

6.3 Acreage enhancement studies
There are other acreage enhancement studies that were undertaken on a speculative basis by several independent consultants that provide further insights into the Deep Atlantic area from several different perspectives. For instance, a piston core survey of the area was undertaken by TDI Brooks International in 2003 and details the presence of live thermogenic hydrocarbons over the acreage. Biostratigraphic Associates Trinidad Ltd has also completed a detailed stratigraphic transect from onshore, through to shallow water and deepwater wells, incorporating the North and East Coast Marine areas, Northern and Southern Basins and Central Range (MEEA, 2012).

The following points therefore need to be evaluated in future deepwater drilling:
1) Many wells reached their TD early because of various well problems.
2) The wells probably drilled the structural plays which turned out to be negligible.
3) There may be need to target the stratigraphic packages off structure.
4) There were limited understanding of the shelf zone and stratigraphy. This is a slope and shelf edge area. It could be a misinterpretation of the shelf zone.
5) Wells encountered gas column in Blocks 25(a) and 26 proving prospectivity of area.

7. Discussions
The impact of currents on deepwater drilling operations could be reduced if there was access to reliable current measurements and/or forecasts. A combination of data sources and numerical modeling should be used by deepwater operators in T&T to provide effective current advisory information for their deepwater campaign. The regulatory body in T&T should require operators to have a current monitor on the rig and the results from monitoring can be compiled in a Meteorological and Oceanographic data set for the country.

Due to North Brazil Current reduced intensity during April-June period (Sharma et al., 2009); it seems that the best period to drill deepwater wells in Trinidad...
is between April and June. Significant currents in the Gulf of Mexico led to the US Minerals Management Service to conduct several current studies. One such study report published in 2008 was the “Deepwater Currents in the eastern Gulf of Mexico” that helped operators drilling deepwater wells in the Gulf of Mexico (Nixon et al., 2009).

Since currents affected the drilling operations, there are several concerns for selection of rigs for deepwater operations in Trinidad. These include high current environment, emergency disconnect capabilities and loop current response time. The rigs used were a semi sub and drill ships. Therefore knowledge of rig motions, station keeping system, riser tensioner system, drift off analysis and ROV deployments are some of the main parameters required for evaluation.

The presence of thermogenic gas found in a couple of wells indicates the existence of a dynamic hydrocarbon system, though still poorly understood. Well 1 encountered several dry gas-bearing sands within massive to finely laminated sandstones. Well 5, though lacking reservoir, did encounter gas in thin sandstone packages. Isotopic analysis of the gas samples suggested a mixture of thermogenic and biogenic components. Well 2 also encountered thermogenic gas. Hydrocarbons were found associated with combination stratigraphic and structural traps, hence validating the trapping mechanisms predicted.

There still remain numerous stratigraphic and structural traps yet to be tested. The eight wells drilled to date have proven a gas-prone younger section, though it is very likely that heavier hydrocarbon components may exist at deeper horizons. This is supported by increasing molecular weight with depth of gas molecules associated with Well 1 (Mullin, 2001). The failure of all wells to reach the intended total depths highlights the challenges of drilling in the basin. However, it is hoped that lessons learned will be carried forward into future drilling in the Deepwater Blocks. If we compare with the Gulf of Mexico experience, since 1975 there have been 285 deepwater discoveries from drilling in excess of 2200 hundred exploration wells and this represents a 1 in 8 chances of success (Nixon et al., 2009).

8. Conclusion and Recommendations

While investigating into the problems, risks and uncertainties encountered during the drilling of wells, several conclusions could be drawn from this study. These are:

1) The actual versus prognosed depths of formation tops were generally very close.
2) 50% of the wells were within the proposed drilling days while 5 of the 8 wells were drilled within budget. None of the wells reached their planned TD.
3) Pore pressures and fracture gradients were generally on the low to medium side of predicted.
4) There were no major environmental incidents.
5) Low gas saturated wet sands and hydrocarbon bearing sands showed similar seismic responses.
6) Data collected can provide calibration of seismic data set and geological model for deepwater, and
7) Some good reservoir quality sands were encountered in most wells.

Future well designs in the deepwater acreage should place more emphasis on overpressure sands, gassy sediments, high pore pressure and gas hydrates could also be encountered. If new well sites are selected, top-hole conditions should be analysed for each new location. New deepwater operators should place more focus on casing and mud plan designs to mitigate and/or contain overpressure sands, and possible gas from the moderate and high-risk zones on the top-hole prognosis. This includes a contingency plan for possible shallow flows from even units assessed with low risk.

MWD logging should be used for the top-hole portion of the well. Besides, drilling pilot holes should be considered before spudding the exploration well especially in Shallow Water Flows (SWFs) prone areas. In addition to objectives of the pilot hole mentioned earlier, this hole could be very useful in direct measurements of formation pore pressure and fracture gradients and gas hydrate accumulations.

The major drilling problems include well control, lost circulation, stuck pipe and well stability and therefore require substantial pre-drill studies, modeling, and real time adjustments to help mitigate these events in the future. Therefore, data from this first deepwater drilling campaign should be used in these future studies.

It is recommended that the best period to drill deepwater wells in Trinidad is April to June. Besides, evaluation of rig motions, station-keeping system, riser tensioner system, drift off analysis and ROV deployments of deepwater is necessary for deepwater drilling operations in Trinidad. A recalibration of the seismic data set should be done and re-divide the deepwater blocks for future exploration work, considering the presence of thermogenic gas in some blocks.

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**Authors’ Biographical Notes:**

**Jerome Rajnauth** is presently a Petroleum Engineer with the Ministry of Energy and Energy Affairs having obtained his PhD from Texas A&M University in December 2010 and his MSc and BSc degrees from The University of West Indies. Apart from sound academic background Dr. Rajnauth has over a dozen years experience in the energy sector having also worked offshore Trinidad, Gulf of Mexico and Venezuela. He has authored and presented over twelve SPE papers as well as other technical papers on the Oil and Gas Industry. He was the recipient of the Trevor Boopsingh Young Engineer award in 2004 and served as Director of Continuing Education on the SPE Trinidad chapter from 2003–2005. Dr. Rajnauth was a member of Technical Committee for the Latin America and the Caribbean Petroleum Exporting Countries Conference held in Trinidad in 2003 and also served as Liaison Officer for 5th Gas Exporting Countries Ministerial Forum in Trinidad in 2005.

**Craig Boodoo** is a Senior Petroleum Engineer with the Ministry of Energy and Energy Affairs, Trinidad and Tobago, with over eleven years experience. Mr. Boodoo studied at The University of West Indies. He has authored, co-authored and presented several technical papers on the Oil and Gas Industry.
Potential Industry Applications Using Gas Hydrate Technology

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Abstract: Over the past decades, gas hydrates have stimulated significant interest and triggered fundamental research. Primarily, the focus has been on hydrate blockage in pipelines, and on naturally occurring gas hydrates. However, gas hydrates can be useful in many different ways that can be pertinent to our industry, thanks to their unique structural packing where only certain molecules can enter the gas hydrate cavities. Among the several potential uses of gas hydrate technology are gas separation, transportation and storage of natural gas, desalination, and carbon dioxide disposal. In particular, it is possible to (i) separate the heavier components (pentane and higher) from natural gas, and (ii) capture, store and transport natural gas. This paper proposes a workflow for capturing, storing and transporting gas in the hydrate form, particularly for situations where there are infrastructural constraints such as lack of pipelines. These applications of gas hydrate technology can have potential benefits to the oil and gas industry.

Keywords: Natural Gas Capture Storage Transportation Hydrate

1. Introduction

Hydrates consist of geometric lattices of water molecules containing cavities occupied by light hydrocarbons and other types of gaseous components such as nitrogen, carbon dioxide, and hydrogen sulfide. Although gas hydrates resemble ice or wet snow, in appearance, but do not have ice’s solid structure, are much less dense and exhibit properties that are generally associated with chemical compounds. Gas hydrates of interest to the natural gas industry are made up of lattices containing water molecules in different ratios with methane, nitrogen, ethane, propane, iso-butane, normal butane, carbon dioxide and hydrogen sulfide. The cavities are at least partially occupied by small gas molecules such as CH\textsubscript{4}, C\textsubscript{2}H\textsubscript{6}, C\textsubscript{3}H\textsubscript{8}, i-C\textsubscript{4}H\textsubscript{10}, n-C\textsubscript{4}H\textsubscript{10}, N\textsubscript{2}, and CO\textsubscript{2} to stabilise the lattice structure.

The need for new methods for gas transportation is the challenge that drives the development of hydrate technology for storing and transporting natural gas (Masoudi, et al., 2005). The ability of natural gas to form hydrate in combination with water is a very interesting and useful concept (Makogon, 1997) and can be widely utilised in the industry. An important feature of hydrates is their high storage capacity. 180 volume units of gas at standard conditions can potentially be packed into 1 volume unit gas hydrate crystals (Sloan, 1997). Gas hydrates can be regarded as a safe and easy way of capturing gas, storing and transporting associated, stranded and flared gas (Berner et al., 2003).

The objective of this work is to propose useful industrial applications that rely on gas hydrate technology, based on selected gas samples (see Table 1). These applications include situations when:

1) Gas storage is required, and so natural gas is converted to gas hydrate and stored for future use.
2) Natural gas hydrate technology provides an attractive method to capture and transport natural gas on a small scale.
3) In the hydrate process of capturing natural gas, heavy components (C\textsubscript{5} and above) are separated out as Natural Gas Liquids (NGL), while C\textsubscript{1} to C\textsubscript{4} are stored in hydrate form.

Table 1. Natural Composition of the gas samples used (Mole %)

<table>
<thead>
<tr>
<th></th>
<th>N\textsubscript{2}</th>
<th>H\textsubscript{2}S</th>
<th>CO\textsubscript{2}</th>
<th>C\textsubscript{1}</th>
<th>C\textsubscript{2}</th>
<th>C\textsubscript{3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Gas</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
<td>99.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Sample 2</td>
<td>0.14</td>
<td>0.21</td>
<td>0.10</td>
<td>0.08</td>
<td>2.82</td>
<td>92.04</td>
</tr>
<tr>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td>2.84</td>
<td>92.04</td>
<td>0.74</td>
<td></td>
</tr>
</tbody>
</table>

The proposed workflow will be discussed using two representative gas samples (‘Dry gas’ and ‘Sample 2’).
The former is basically pure methane, whereas sample 2 has the heavier C5 and C6 components. It is assumed that these gases are produced from a given field, at a given rate.

Most of the previous studies focused on simple gases with composition of primarily methane and ethane to form gas hydrate. Most natural gas has much more components than just methane and ethane and hence the composition can have significant impact on hydrate formation. For this reason, this analysis showed a dry gas sample and sample 2 with heavier components. The overall study looked at over 20 natural gas samples with varying composition.

In this study, the PVTSim program (Calsep, 2008) was used for the evaluation of hydrate formation and expansion processes. Expansion of the gas from wellhead conditions is necessary to trigger hydrate formation, depending on the properties of the gas, as it will be shown in this analysis with the two selected samples. Hydrate formation conditions of 600 psia and 35°F are assumed, based on laboratory studies conducted by Okutani et al., (2007) who used methane, which is close to the dry gas sample used in the present work.

In the hydrate formation process, only the C1 to C4 alkane components of natural gas are captured. C5 and higher components are separated out as natural gas liquids. This is a particularly useful concept, especially in cases when the lighter components of natural gas are needed for power generation, and the heavier components can have a negative impact on gas turbines. This concept is illustrated with the Sample 2 case.

The formation of natural gas hydrate yields a high latent heat of formation that must be removed to prevent dissociation. To this aim, the formation vessel could be equipped with heat exchange tubes, extending the full length of the vessel, to facilitate heat transfer from the vessel. The heat exchange tubes not only aid the heat removal process - they also (i) supply heat for later dissociation of hydrate, after formation and storage/transportation, and (ii) provide additional surface area for more effective hydrate formation.

The focus of the study is to evaluate forming gas hydrate as soon as the gas comes from the well. Whether it is offshore or onshore the hydrate vessels will be position there to capture the natural gas from the well. Other studies focused on gas being transported to a hydrate plant for hydrate conversion and therefore the conditions using gas directly from the well in this analysis are different from other evaluations. Therefore, it is proposed that the same vessel used to form the hydrate be also used for storage and transport to its delivery point.

The “one vessel” concept is very useful to avoid moving the solid hydrate from vessel to vessel for storage and transportation, reduce costs, since no additional facility is needed for dissociation at the final destination, and allow water re-cycling. Using one vessel for formation, storage, transportation and dissociation of the hydrates gives operational flexibility for temporary storage and transportation. In the absence of pipeline infrastructure, hydrates could be transported in the vessel, by truck, railway or ship.

2. Dry Gas Sample Analysis

The process flow in Figure 1 illustrates the capture of 5 MMSCF of dry gas from one producing well in hydrate form. The wellhead conditions are considered to be 1,750 psia and 168 °F. From the wellhead, the gas flows through a turbo-expander, which causes the gas temperature to drop to 35 °F, and the pressure to drop to 600 psia, assuming an efficiency of 85% (note that some commercial expanders can exhibit up to 90% efficiency). These new pressure and temperature values represent the inlet conditions to the hydrate reactor vessel. Note the heating value of the dry gas is the same before and after hydrate formation (1,018 btu/ft³).

The sample’s heating value was estimated from the heating values of the sample’s components, using the composition shown in Table 2. The amount of water required for the process was estimated at 6.29:1 mole ratio of water to gas for the Dry gas sample. This was determined from a sensitivity analysis using several samples with varying composition, and discussed in a previous paper (SPE 131663). A total of 4,261 bbls of water is therefore required to capture the 5MMSCF of gas.

![Figure 1. Gas Hydrate Process Flow for the Dry Gas Sample](image-url)
Table 2. Heating Value Estimation for Dry Gas Sample

<table>
<thead>
<tr>
<th>Sample Dry gas</th>
<th>Ideal Heating Value</th>
<th>Heating Value Gas mix in Hydrate</th>
<th>Heating Value Gas mix before hydrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane C1</td>
<td>99.00</td>
<td>1010.0</td>
<td>999.9</td>
</tr>
<tr>
<td>Ethane C2</td>
<td>1.00</td>
<td>1769.7</td>
<td>17.7</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>1018</td>
<td>1018</td>
</tr>
</tbody>
</table>

Figure 2 shows the expansion process with corresponding energy exchange for the ideal process (isentropic and 100% efficient) and for the actual process at various expander efficiencies. The secondary axis of the graph is the outlet temperature that corresponds to a given efficiency. The figure presents the variation in enthalpy and entropy for the expansion process considering several expansion efficiencies. At 100% efficiency (Isentropic process), entropy is constant but the value increases as efficiency decreases. The work the gas performs is gained from its enthalpy and the gas cools rapidly in the expander. The expansion process must also ensure the gas remains in the gaseous phase.

\[ \text{Power}_{\text{expander}} = \Delta h \times w \times \eta_e \]

Where:
- \( \Delta h \) = change in enthalpy, btu/lbmole, obtained from Figure 2.
- \( w \) = flow rate, lbmole/hr
- \( \eta_e \) = expander efficiency, %

For an 85% efficiency, \( \Delta h = 903.1 \text{ btu/lbmole} \) and \( w = 550 \text{ lbmole/hr} \)

Table 3. Horse Power Generated and Outlet Temperature for various expansion efficiencies

<table>
<thead>
<tr>
<th>Efficiency %</th>
<th>Power (btu/hr)</th>
<th>Outlet Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>584375.0</td>
<td>19.4</td>
</tr>
<tr>
<td>95</td>
<td>527359.3</td>
<td>25</td>
</tr>
<tr>
<td>90</td>
<td>473319.0</td>
<td>30.3</td>
</tr>
<tr>
<td>85</td>
<td>422199.3</td>
<td>35.5</td>
</tr>
<tr>
<td>80</td>
<td>374000.0</td>
<td>41.3</td>
</tr>
</tbody>
</table>

Figure 3 shows the phase diagram for Dry Gas sample, with the wellhead and outlet conditions for varying expansion efficiencies. It can be seen that gas remains in the gas phase region during the expansion process. Note that this sample is mainly pure methane and does not exhibit a phase envelope.

3. Sample 2 Analysis

The process flow in Figure 4 illustrates the capture of 5 MMSCF of Sample 2 gas in hydrate form. The computed heating value of the gas was 1,029 btu/ft\(^3\) before the hydrate formation, and 1,014 btu/ft\(^3\) after. This is because the hydrate formation separates the heavier components (> C5) as useful natural gas liquid. 0.02 MMSCF (3,829 bbls) of natural gas liquids are obtained with a heating value of 4,441 btu/ft\(^3\) while 4.98 MMSCF natural gas (C1 to C4) is stored in hydrate form.

The estimations of the heating values of the gas prior to hydrate formation and the heating values transported in hydrate form for both samples were important to determine gas acceptance at markets around the world or whether further gas processing required (see Table 4). The heating value was calculated simply by...
multiplying the ideal heating values of the individual component by the mole fraction which gives a simply approximation. This may vary from measured values.

![Figure 4. Gas Hydrate Process Flow for Sample 2](image)

**Table 4. Estimation of Heating Value of Sample 2 before hydrate formation**

<table>
<thead>
<tr>
<th>Sample 2 before hydrate formation</th>
<th>Ideal Heating Value</th>
<th>Gas mix before hydrate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mol %</td>
<td>btu/ft³</td>
</tr>
<tr>
<td>Nitrogen N₂</td>
<td>0.78</td>
<td>0.0</td>
</tr>
<tr>
<td>Carbon Dioxide CO₂</td>
<td>2.84</td>
<td>0.0</td>
</tr>
<tr>
<td>Methane C₁</td>
<td>92.04</td>
<td>1010.0</td>
</tr>
<tr>
<td>Ethane C₂</td>
<td>2.82</td>
<td>1769.7</td>
</tr>
<tr>
<td>Propane C₃</td>
<td>0.74</td>
<td>2516.1</td>
</tr>
<tr>
<td>Isobutane iC₄</td>
<td>0.14</td>
<td>3251.9</td>
</tr>
<tr>
<td>N-Butane nC₄</td>
<td>0.21</td>
<td>3262.3</td>
</tr>
<tr>
<td>Isopentane iC₅</td>
<td>0.08</td>
<td>4008.9</td>
</tr>
<tr>
<td>N-Pentane nC₅</td>
<td>0.25</td>
<td>4755.9</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>4000.9</td>
</tr>
</tbody>
</table>

Table 5 estimates the heating value of the gas before hydrate formation. Table 5 estimates the heating value of the gas captured in the hydrate, and Table 6 estimates the heating value of the Natural Gas liquids that is not captured in the hydrate. The accepted heating value range accepted in the US is in the range 966 – 1,120 Btu/scf. For Europe, the range is 940–1204 Btu/scf and for Japan 1,065 - 1,160 Btu/scf is required.

The amount of water required for the process was estimated at 6.264:1 mole ratio of water to gas. A total of 4220 bbls of water is therefore required to capture 4.98MMSCF of gas.

The actual wellhead conditions in this case are 1,800 psia and 173°F which is slightly different from the Dry Gas Sample. The expansion turbine extracts the potential heat energy from the gas, causing it to cool drastically from 173°F to 35°F.

Figure 5 shows the expansion process with corresponding energy exchange for the ideal and the actual processes. The power developed by the expander and the outlet temperatures are shown in Table 7. At least 90% efficiency is required to have an outlet temperature of 35°F required for hydrate formation in this case. This generates 1.29 x 10⁷ Btu of useful energy.

![Figure 5. Expansion Process for Dry Gas Sample](image)

**Table 5. Estimation of Heating Value of Sample 2 after hydrate formation**

<table>
<thead>
<tr>
<th>Sample 2 after hydrate formation</th>
<th>Ideal Heating Value</th>
<th>Gas mix in hydrate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mol %</td>
<td>btu/ft³</td>
</tr>
<tr>
<td>Nitrogen N₂</td>
<td>0.78</td>
<td>0.0</td>
</tr>
<tr>
<td>Carbon Dioxide CO₂</td>
<td>2.85</td>
<td>0.0</td>
</tr>
<tr>
<td>Methane C₁</td>
<td>92.44</td>
<td>1010.0</td>
</tr>
<tr>
<td>Ethane C₂</td>
<td>2.83</td>
<td>1769.7</td>
</tr>
<tr>
<td>Propane C₃</td>
<td>0.74</td>
<td>2516.1</td>
</tr>
<tr>
<td>Isobutane iC₄</td>
<td>0.14</td>
<td>3251.9</td>
</tr>
<tr>
<td>N-Butane nC₄</td>
<td>0.21</td>
<td>3262.3</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>4000.9</td>
</tr>
</tbody>
</table>

**Table 6. Estimation of Heating Value of Natural Gas Liquids**

<table>
<thead>
<tr>
<th>Natural Gas Liquids</th>
<th>Ideal Heating Value</th>
<th>NGL Heating Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isopentane iC₅</td>
<td>23.3</td>
<td>0.0</td>
</tr>
<tr>
<td>N-Pentane nC₅</td>
<td>18.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Hexanes C₆</td>
<td>58.1</td>
<td>1010.0</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>1769.7</td>
</tr>
</tbody>
</table>

**Table 7. Horse Power Generated and Outlet Temperature for various expansion efficiencies**

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Power</th>
<th>Outlet Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>btu/h</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>593615.0</td>
<td>23.14</td>
</tr>
<tr>
<td>95</td>
<td>536294.0</td>
<td>28.33</td>
</tr>
<tr>
<td>90</td>
<td>481338.0</td>
<td>33.61</td>
</tr>
<tr>
<td>85</td>
<td>429352.0</td>
<td>38.91</td>
</tr>
<tr>
<td>80</td>
<td>380336.0</td>
<td>44.22</td>
</tr>
</tbody>
</table>
Figure 6 shows the phase diagram for the Dry Gas sample with wellhead and outlet conditions, and with varying expansion efficiencies. Note that at 100% efficiency, the gas is very close to the two-phase region.

Therefore, the selected expander efficiency must allow the expansion of the gas to the required hydrate formation conditions and ensure that the gas remains in the single gas phase after expansion. If the gas sample does not remain in the single phase after expansion (two phase region), then this gas sample is not an appropriate candidate using this method. Additional separation facilities would then be required.

4. Hydrate Formation

The next stage after gas expansion/cooling is the hydrate formation. Natural gas from the expander, together with cold water, enters the reactor vessel at 35°F, and approximately 29,831 ft³ of hydrate is formed. The formation of natural gas hydrate yields a high latent heat of formation which must be removed to prevent dissociation. For 5 MMSCF of natural gas, 3.15 x 10⁸ Btu must be removed. To achieve this, the formation vessel could be equipped with heat exchange tubes extending the full length of the vessel to enable effective removal of heat through the vessel. Figure 7 shows the end view of the vessel with heat transfer tubes.

Heat from the surrounding can transfer into the formation vessel and increase its temperature, causing dissociation of the hydrate as it forms. Insulation (e.g. NanoPore) is therefore necessary to minimise heat transfer with the surroundings. NanoPore thermal insulation provides exceptional performance with a very low overall thermal conductivity of 0.004 btu.in/ft².h.F. Because of its unique pore structure, NanoPore thermal insulation can provide thermal performance greater than conventional insulation materials (www.nanopore.com). About 240 btu/h of heat gained from the surroundings must be removed when using 1” thickness NanoPore material, compared to 4.35 x 10⁷ btu/hr without any insulation.

It is proposed that the same vessel used to form the hydrate could also be used for storage and transport to its delivery point, whether the gas is for domestic use or international markets.

The natural gas composition may have heavier components (C₅ or higher), as in the case of Sample 2. In the hydrate formation process, only C₁ to C₄ are captured, and the higher components (C₅ and higher) separate in the process as natural gas liquids (NGL). This is not the case with the Dry gas sample, which is primarily methane, with 1% ethane. Figure 8 shows the density difference between water, hydrate and NGL during the process.

This separation method can be very useful for capturing lighter components necessary for efficient power generation. Some small amounts of higher components might have a negative effect on gas turbine systems. According to Ginter et al. (2001), there are problems with the presence of higher molecular weight components found in natural gas, as they can condense at low temperature, and appear as droplets in fuel supply, thus increasing the tendency for self-ignition. This also affects the flame position and combustion.
stability. This is an important industrial application of the hydrate technology where heavy components from C5 up are separated in the hydrate formation process. There is no need for gas processing prior to hydrate formation unless there is a significant amount of CO2 or H2S in the sample.

Once the hydrate formation is complete, temporary storage or transportation may be required.

5. Storage and Transportation

If gas storage is required, the same formation vessel could be used to store the hydrate. This is another potential application of gas hydrate technology where gas can be temporarily stored until later use. Depending on the storage time, additional cooling will be required to remove heat gain from the surroundings. Heat gain at a rate of 240 Btu/hr must be removed. To this aim, the fixed heat transfer tubes in the vessel can be used, in combination with a small refrigeration unit. Figure 9 shows the conceptual storage system of gas hydrate, which can be used for possible gas storage for land-based power plants. Several storage vessels could be stacked side by side while awaiting hydrate dissociation to provide natural gas for uses such as power generation.

Transporting gas hydrate can be done both by land and by sea in order to deliver natural gas. This option uses the hydrate technology to transport gas to markets. A small refrigeration system may be required to remove heat gained from the surroundings. The same formation vessel can be used to transport hydrate using a trucking system (see Figure 9). For remote fields, where only railroad transportation is available, gas hydrate could be transported by train in the formation vessels.

For transportation by sea, the hydrate storage vessels could be placed in a container for protection, and transported to small-scale markets for short to medium distances (see Figure 9). According to Gudmundsson et al. (1998), natural gas hydrate transportation by sea is best suited for distances up to 12,000 km.

6. Dissociation

The final stage in the proposed workflow is dissociation, when the hydrate conditions are altered to return natural gas and water. This dissociation stage is done using the heat exchange tubes to transfer heat to the hydrate, causing re-gasification.

The dissociation time at the market is another key aspect to the overall gas hydrate value chain. Dissociation of the hydrate can be done through depressurisation of hydrate or increasing temperature of the hydrate. In this study we only consider hydrate dissociation by increasing temperature. Faster dissociation rates would be facilitated by the heat transfer tubes that traverse the entire vessel. Therefore hot water can be pumped through the heat exchange tubes in the vessel (see Figure 7) to facilitate hydrate dissociation. The same amount of heat of formation removed during hydrate formation is required to dissociate the hydrate to gas and water. In this case, $3.15 \times 10^8$ Btu must be supplied to dissociate the 29,831 ft$^3$ of hydrate. The hot water is not transported with the hydrate but will be available at the market. There are several options using available seawater or disposed water. Water at 80°F can be appropriate to dissociate the hydrate (at 35°F) utilising the heat transfer tubes. In fact the analysis showed that the hydrate can be dissociated in 3.6 hours using water at 80°F pumped through the tubes. However, detail analysis of this will be published as another part of the entire study.

8. Conclusion

Several conclusions are drawn for the study. They are summarised below:

1) The expansion process yields useful energy that can be used in many ways, including power generation.
2) The expansion efficiency required to obtain the natural gas at 35°F may vary from sample to sample. In this case, for dry gas sample, 85% efficiency was required, whereas 90% efficiency was needed for sample 2. Some commercial expanders can have up to 90% expansion efficiency.
3) The expansion process must also ensure the gas sample remains in the single-phase region of the phase diagram, which is important in the design process.
4) Heat removal from hydrate formation can be achieved by using fixed tubes placed in the formation vessels. These tubes can also be used to remove heat gained from the surroundings during hydrate storage or transportation.
5) The fixed tubes can also be used to supply heat for subsequent hydrate dissociation.
6) The hydrate formation process separates out C5 and higher as natural gas liquids, and captures C1 to C4. This is particularly important in cases where light
components are needed for power generation.
7) Gas hydrate can be used as a form of natural gas storage for future use, as in the case of power plants.
8) Insulation is required to reduce heat transfer into the vessel. NanoPore thermal insulation could provide superior performance for the vessel.
9) Using one vessel for hydrate formation, storage, transportation and dissociation could provide significant flexibility and hardware cost reduction.
10) Transportation of natural gas in the form hydrate by trucks, railway and sea can be considered especially in the absence of pipeline infrastructure.

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A Method for Predicting the Phase Behaviour of Trinidad Gas Condensates

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Abstract: Gas condensate compositional simulation studies are conducted to evaluate gas and condensate reserves. This is carried out when making comparisons of production methods for the economic development of a reservoir. The experimental data needed for the evaluation are dew point pressure, gas compressibility factor (z factor), liquid volume and produced gas (Constant Volume Depletion, CVD data) and are nowadays determined from a tuned Equation of State (EOS). However, the open literature has shown that there is no consistency in the number of Single Carbon Number (SCN) groups, EOS tuning parameters, lumping schemes and weight factors applied to the experimental data when tuning an EOS for use in compositional simulation studies, particularly for gas condensate fluids. Publications have shown that the two most widely used sets of parameters from the EOS that are tuned are the Binary Interaction Coefficient (BIC) with the critical properties and acentric factor or BIC and the EOS coefficients called the omegas (Ω). The number of SCN groups used for tuning varies from ten to more than forty. However, there are currently no criteria for selecting the most reliable lumping scheme that will give similar accuracy to using the many SCN groups except by trial and error or by algorithms designed to test a number of schemes and from which the best one is selected. In this paper, the Peng-Robinson EOS has been tuned and tested to predict CVD data for six Trinidad gas condensate samples. Compositional analysis greater than Single Carbon Number 24 (SCN24) is required for the SCN route. The two sets of tuning parameters were used with and without the volume shift parameter (VSP). Our parametric study demonstrated that the VSP should not be applied with the Ωs when tuning the Peng-Robinson EOS. With weight factors of 1 for liquid volume, 10 for gas compressibility factor and without the VSP, the Ωs give better prediction of CVD data than the critical properties and acentric factor even with the VSP included. The SCN groups for one sample were lumped into six Multiple Carbon Number (MCN) groups using the simple Whitson’s lumping scheme. Our tuning technique with the Ωs and with our new weight factors for the experimental data, gave differences of less than ±4.0 % from the tuned EOS predictions before and after lumping of the SCN group so that complex algorithms are not necessary to select an appropriate lumping scheme to reduce cost and computer time when performing simulation studies. The tuning technique with only one regression step, showed consistency in tuning the Peng-Robinson EOS with the Ωs and could be used for simulation studies of Trinidad gas condensate systems.

Keywords: Gas Condensate, Equation of State, tuning parameters, weight factors, Trinidad

1. Introduction

Gas condensate field development planning requires compositional simulation studies using a tuned Equation of State (EOS) for the evaluation of gas and condensate reserves, production methods, facilities design as well as economic development (Coats et al., 1986; Pedersen et al., 1989; Danesh, 1998). The physical property data needed for such evaluation are dew point pressure, gas compressibility factor, liquid volume and produced gas (Constant Volume Depletion, CVD data).

Tuning involves adjustment of groups or sets of the most difficult to measure EOS parameters so as to minimise the difference between predicted and measured PVT data (Agarwal and Nghiem, 1990). Al-Sadoon and Almarry (1985) demonstrated the success of tuning by regression with binary interaction coefficient (BIC), between methane and the heavy fractions (greater than hexanes and including the plus fraction) and the critical pressure, P_c, critical temperature, T_c and acentric factor, ω, for the plus fraction. Demonstrations by Coats et al (1986) were with BIC between methane and the heavy fractions and the Ωs (omegas of methane and omegas of the plus fraction) for various reservoir fluids. Unicamp and Rodriguez (1992) tuned the Peng Robinson (1976)
EOS first with the tuning parameters selected by Al-Sadoon and Almarry (1985) and then with the parameters selected by Coats et al. (1986) to predict dew point pressure, produced gas and gas compressibility factor with errors of less than 10%. The prediction of liquid volume was not included in their demonstration.

Danesh (1998) pointed out that the volume shift parameter (VSP) (Jhaveri and Youngren, 1984) should also be included as a tuning parameter to improve the accuracy in the prediction of liquid volume and to assign a weight factor of 40 to dew point pressure and 10 to liquid volume. However the open literature did not demonstrate if the VSP and suggested weight factors should be used with BIC, P_c, T_c and ω or with BIC and the Ωs.

The data required for the physical property prediction by any EOS are pressure, temperature and composition. The composition of a sample is experimentally determined by gas chromatography and components heavier than pentanes are lumped into Single Carbon Number (SCN) groups (Katz and Firoozabadi, 1978; Pedersen et al., 1989; Hosein, 2004; Hosein and Dawe, 2011). The last group is known as the plus (C+) or last fraction. Prior to tuning, the number of SCN (Single Carbon Number) groups required to converge the EOS predicted values to the experimentally measured values is determined (Pedersen et al., 1989; Danesh, 1998). Often extended analysis of the plus fraction (Pedersen et al., 1989; Hosein and McCain 2009) from as low as SCN10 (Coats et al., 1986) to as high as SCN45 (Al-Meshari and McCain, 2007) has been reported as needed for this step. Studies have shown that after performing this step, minimal tuning of the EOS parameters is required (Pedersen et al., 1989; Danesh 1998; Hosein 2004).

However, in order to reduce simulation costs and computing time, lumping schemes (Whitson, 1980, Behrens and Sandler 1986; Ahmed 1989; Pedersen et al 1989; Danesh, 1998) to reduce the number of SCN groups into three to five Multiple Carbon Number (MCN) groups (pseudo-components) are used.

The number of MCN groups required and the distribution of SCN groups within each MCN group can be calculated by a simple form (e.g. Whitson (1980)) or more complex lumping forms (e.g. Behrens and Sandler (1986)). Currently, there are no standard criteria for selecting the best lumping scheme to give similar accuracy as can be calculated by the many SCN groups, except by trial and error or by algorithms (Danesh, 1998; Kai, 2001) designed to test a number of schemes. The best one is then selected.

All cubic EOS have a theoretical inherent deficiency in predicting liquid volume away from the critical point and require some degree of tuning especially for gas condensate systems (Pedersen et al., 1989). In the Petroleum Industry, the Soave Redlich Kwong (SRK) (Soave, 1972) and the Peng Robinson (1976) are the two most widely used (Danesh, 1998). Although the selection between the two is a matter of user preference, the Peng Robinson (1976) EOS was developed to improve the prediction of liquid volume (see Appendix for details) in comparison to the SRK and the degree of tuning required should also be less than the SRK (Ahmed, 1986; Danesh 1998).

In this paper a parametric method for tuning the Peng-Robinson (1976) EOS to accurately predict CVD data without the VSP is presented, using a range of components, tuning parameters and weight factors for the experimental data that gave acceptable predictions of CVD data for six Trinidad gas condensate samples. We use the Whitson (1980) lumping scheme to demonstrate that our tuning technique gives minimal differences before and after lumping (Hosein, 2004). Hence complex algorithms are not necessary to select an appropriate lumping scheme.

2. Thermodynamic Model and Fluid System

Trinidad gas (condensate) reservoirs are located offshore the Southeast coast and the North coast. Our tuning technique was demonstrated using six samples which were taken from each of the gas condensate fields and were analysed by Hosein (2004) as follows:

2.1 Sample Composition and Properties of the SCN Groups and the Plus Fractions

The compositions of the samples were obtained by gas chromatography and are shown in Appendix 1, Table A1. These are lean gas condensates with mole % of the C_7+ ≤ 4% (McCain, 1990). The Specific gravity and molecular weight of the SCN groups (see Table A1) were taken from charts published by Katz and Firoozabadi, (1978), as suggested by Hosein and Dawe (2011). Similar properties for the plus fractions were determined experimentally after performing True Boiling Point (TBP) analysis (Hosein, 2004, Hosein and Dawe, 2011). The EOS parameters P_c, T_c and ω for the SCN groups and the plus fractions were determined from correlations published by Kesler and Lee (1976) and Lee and Kesler (1980). The splitting of the C_20+ fraction was performed using the gamma distribution function (Whitson, 1983) as described by Al Mesharri and McCain (2007) for gas condensate systems.

2.2 PVT Data (see Appendix 2)

Gas condensate PVT studies were conducted using the PVT facilities at The University of the West Indies (UWI) (Hosein, 2004). These data are shown in Table A2. The sample validity and accuracy of the sample compositions and PVT data were evaluated in the same study by Hosein (2004).

2.3 The Peng-Robinson (1976) EOS and Tuning Parameters (see Appendix 1)

The Peng-Robinson (1976) EOS was separately tuned using the sets of tuning parameters studied by Al-Sadoon
and Almarry (1985) and by Coats et al. (1986) and then repeated by including the VSP as suggested by Danesh (1998). The default values for $\Omega_a$ and $\Omega_b$ were 0.4572 and 0.0778, respectively (WINPROP, 2002). The correlation published by Oellrich et al. (1981) was used for obtaining BIC between methane and the heavy fractions as follows:

$$
BIC = 1 - \left( \frac{2V_{c_i}^{1/3}V_{c_j}^{1/3}}{V_{c_i}^{1/3} + V_{c_j}^{1/3}} \right)^n
$$

(1)

where $V_{ci}$ and $V_{cj}$ are the critical volumes of component $i$ and component $j$. BIC was evaluated by tuning the Hydrocarbon Interaction Coefficient Exponent (HICE), $n$. An exponent value of 1.2 was used as a starting value (WINPROP, 2011). The upper and lower bounds for the tuning parameter were set to allow a change of ±20% of the test values so as to ensure that they remain physically reasonable (WINPROP, 2011). For HICE the bounds were set (between 0.0 and 1.8) which are the limits appropriate for typical petroleum fluids (WINPROP 2011).

### 2.4 Tuning by Regression

Experimental PVT data (Appendix 1, Table A2) were used together with a multi-variable regression scheme (WINPROP 2011) whereby the selected set of EOS parameters was adjusted until a minimum difference between predicted and experimental values was attained (Agarwal and Nghiem, 1990). Each regression was performed in a single step by minimising the objective function $F$ (Dennis et al., 1981), as follows:

$$
F = \sum_{i=1}^{N} \left[ \frac{w_i (y_{i,\text{pred}} - y_{i,\text{expt}})}{y_{i,\text{expt}}} \right]^2
$$

(2)

where $y_{i,\text{pred}}$ and $y_{i,\text{expt}}$ correspond to the predicted and experimental CVD values respectively. The weight factors, $w_i$, assigned to the experimental data for testing are shown in Table 1. The weight factor of 10 for liquid volume was suggested by Danesh (1998). The weight factors of 1 for liquid volume and 10 for gas compressibility factor were determined in this study by trial and error for tuning with the $\Omega$s.

### Table 1. Average Absolute Deviation between Peng-Robinson (1976) EOS Pred. and Expt. Liquid Volume and Gas Compressibility Factor with and without the Volume Shift Parameter for published and tested Weight Factors and with analyses greater than SCN24

<table>
<thead>
<tr>
<th>Options and Tests</th>
<th>AAD (%) in Liquid Vol.</th>
<th>AAD (%) in Z Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Published Weight Factor</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>After Tuning Set A, with VSP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Option A</td>
<td>&lt;12</td>
<td>&lt;3</td>
</tr>
<tr>
<td>After Tuning Set A, without VSP</td>
<td>Test A1</td>
<td>&lt;25</td>
</tr>
<tr>
<td>After Tuning Set B, with VSP</td>
<td>Test B2</td>
<td>&lt;12</td>
</tr>
<tr>
<td>After Tuning Set B, without VSP</td>
<td>Test B3</td>
<td>&lt;10</td>
</tr>
<tr>
<td><strong>Tested Weight Factor</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>After Tuning Set B, without VSP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Option B</td>
<td>&lt;10</td>
<td>&lt;3</td>
</tr>
<tr>
<td>After Tuning Set B, with VSP</td>
<td>Test B1</td>
<td>&lt;15</td>
</tr>
<tr>
<td>After Tuning Set A, without VSP</td>
<td>Test A2</td>
<td>&lt;30</td>
</tr>
<tr>
<td>After Tuning Set A, with VSP</td>
<td>Test A3</td>
<td>&lt;20</td>
</tr>
</tbody>
</table>

**Legends:**
ADD = Average Absolute Deviation; DPP = Dew Point Pressure; Z factor= Gas Compressibility Factor; LDO = Liquid Volume
PG = Produced Gas; VSP = Volume Shift Parameter;
Set A = BIC and $P_c$, $T_c$ and to for the plus fraction
Set B = BIC, $\Omega_a$ and $\Omega_b$ for methane and $\Omega_a$ and $\Omega_b$ for the plus fraction

### 3. Simulation of Constant Volume Depletion (CVD) Data

#### 3.1 EOS Predictions

Figure 1 shows the average absolute deviations (see Eq. 3) between Peng-Robinson (1976) EOS predicted and experimental CVD data for all samples, with increasing analysis to $C_{7+}$, $C_{11+}$, $C_{15+}$, $C_{20+}$, $C_{25+}$, and $C_{30+}$. The deviations (as defined below) were in the range 10 to 30% for dew point pressures (DPP), 50 to 100% for liquid volume (LDO) and 20 to 40% for produced gas (PG).

Average Absolute Deviation (AAD in %)

$$
\text{AAD} = \frac{1}{n} \times \sum_{i=1}^{n} \left| \frac{y_{i,\text{pred}} - y_{i,\text{expt}}}{y_{i,\text{expt}}} \right| \times 100 \%
$$

(3)

These results show that the EOS has limitations and cannot produce a set of minimum deviations for any of the plus fraction range studied. It is showed that the gas compressibility (Z) factor was accurately predicted with a deviation of less than 4%.
The challenge faced was how to improve the predictions of dew point pressure, liquid volume and produced gas after tuning the Peng-Robinson (1976) EOS with a defined range of components, tuning parameters and weight factors for best possible accuracy.

3.2 Peng-Robinson (1976) EOS Predictions after Tuning BIC and the heavy fractions and Pc, Tc and ω for the plus fraction (Al-Sadoon and Almarry 1985).

3.2.1 Tuning with the VSP and a weight factor of 10 for liquid volume (Option A)

Figure 2 shows the average absolute deviations (see Eq. 3) between Peng-Robinson (1976) EOS predicted and experimental CVD data for all samples, with increasing analyses as described above (see also Table 1). For analyses up to C_{25+}, predictions of CVD data were obtained, with deviations lower than 5% for dew point pressure (DPP), lower than 12 % for liquid volume (LDO), lower than 10 % for produced gas (PG) and lower than 2% for gas compressibility (Z) factor.

These results were obtained with the VSP and by applying a weight factor of 10 for liquid volume as suggested by Danesh (1998) and 40 for dew point pressure as suggested by Coats et al. (1986). These results were obtained for the six samples studied which demonstrate consistency in tuning the Peng-Robinson (1976) EOS.

3.2.2 Tuning without the VSP and a weight factor of 10 for liquid volume (Test A1)

Without the VSP the prediction of liquid volume is less accurate than option A with deviations higher than 12% but lower than 30% (see Table 1).

3.2.3 Tuning without the VSP and a weight factor of 1 for liquid volume and 10 for Z factor (Test A2)

Without the VSP and with a weight factor of 1 for liquid volume and 10 for gas compressibility factor, the prediction of liquid volume is less accurate than option A with deviations higher than 12% but lower than 20% (see Table 1).

3.3 EOS Predictions after Tuning Parameter BIC for the heavy fractions, Ω_a and Ω_b for methane and Ω_a and Ω_b for the Plus Fraction (Coats et al 1986).

3.3.1 Tuning without the VSP and a weight factor of 1 for liquid volume and 10 for Z factor (Option B)

Figure 3 shows the average absolute deviations between Peng-Robinson (1976) EOS predicted and experimental CVD data for all samples with increasing analyses as described earlier (see also Table 1). For analyses up to C_{25+}, and up to C_{30+}, predictions of CVD data were obtained, with deviations lower than 3% for dew point pressures (DPP), lower than 10% for liquid volume (LDO), lower than 5% for produced gas (PG) and lower than 3% for gas compressibility (Z) factor.

These results were obtained without the VSP and by applying a weight factor of 1 for liquid volume as suggested by Coats et al. (1986). These new weight factors were determined by trial and error and are applicable for the Ωs only. The published weight factor of 40 was used for dew point pressure as suggested by Coats et al. (1986).

This new information on tuning the EOS with the Ωs was not found in the open literature. This new information when applied, shows consistency in tuning the EOS with the Ωs and gives more accurate predictions.
than option A (BIC, Pc, Tc and ε, with VSP included).

3.3.2 Tuning with the VSP and a weight factor of 1 for liquid volume and 10 for Z factor (Test B1)

With the VSP and with a weight factor of 1 for liquid volume and 10 for gas compressibility factor, the prediction of liquid volume although acceptable was less accurate than option B with deviations higher than 10 % but lower than 15 % (see Table 1).

3.3.3 Tuning with the VSP and a weight factor of 10 for liquid volume (Test B2)

With the VSP and with a weight factor of 10 for liquid volume the prediction of gas compressibility factor was less acceptable than option B with deviations higher than 3 % but lower than 10 % (see Table 1). The prediction of liquid volume, although being acceptable, was less accurate than option B with deviations higher than 10 % but lower than 12 %.

3.3.4 Tuning without the VSP and a weight factor of 10 for liquid volume (Test B3)

Without the VSP and with a weight factor of 10 for liquid volume, the prediction of gas compressibility factor was less acceptable than option B with deviations higher than 3 % but lower than 10 % (see Table 1). The prediction of liquid volume, although being acceptable, was less accurate than option B with deviations higher than 10 % but lower than 12 %.

4. Tuning of the Peng-Robinson (1976) EOS before and after Lumping

Our tuning technique with the Tuning Parameters BIC for the heavy fractions, \( \Omega_a \) and \( \Omega_b \) for methane and \( \Omega_a \) and \( \Omega_b \) for the plus fraction, weight factors of 40 for dew point pressure 1 for liquid volume and 10 for Z factor was applied to all samples. This is to compare predictions before and after lumping as follows:

The compositions of the gas condensate samples PL1 to PL6 (taken from Hosein 2004) were lumped using Whitson’s (1980) lumping scheme (see Table 2) and were tuned to predict dew point pressure, gas compressibility factor, liquid volume and produced gas.

The Average Absolute Deviations between the tuned EOS (Peng-Robinson, 1976) predicted data before and after lumping were less than 2.0 % for all samples studied as shown in Table 3. These results indicate that the Whitson’s (1980) lumping scheme when applied with our tuning technique can give accurate, and similar, predictions to those obtained before lumping.

5. Tuning Procedures

A set of step-by-step tuning procedures is derived from this study. These are:

1. Analyse experimentally the well-stream compositional data range to between \( C_{25} \) and \( C_{30} \) and input into the software (e.g., WINPROP, PVTi, etc.).

2. If the available experimental compositional is lower than this range, then extend the plus fraction using the gamma distribution function (Whitson, 1983).

3. If the available experimental compositional is lower than this range, then extend the plus fraction using the gamma distribution function (Whitson, 1983). (This option is available in the software).

<table>
<thead>
<tr>
<th>MCN Groups</th>
<th>Symbol</th>
<th>PL1</th>
<th>Specific Gravity</th>
<th>Molecular Wt., g/mol</th>
<th>MCN Groups</th>
<th>Symbol</th>
<th>PL2</th>
<th>Specific Gravity</th>
<th>Molecular Wt., g/mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCN7 to SCN9</td>
<td>MCN1</td>
<td>1.841</td>
<td>0.748</td>
<td>107</td>
<td>SCN7 to SCN9</td>
<td>MCN1</td>
<td>1.360</td>
<td>0.747</td>
<td>106</td>
</tr>
<tr>
<td>SCN10 to SCN12</td>
<td>MCN2</td>
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<td>MCN4</td>
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<td>0.856</td>
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<td>MCN4</td>
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<th>Specific Gravity</th>
<th>Molecular Wt., g/mol</th>
<th>MCN Groups</th>
<th>Symbol</th>
<th>PL4</th>
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<td>0.791</td>
<td>144</td>
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<td>MCN2</td>
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<td>SCN17 to SCN21</td>
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<th>Specific Gravity</th>
<th>Molecular Wt., g/mol</th>
<th>MCN Groups</th>
<th>Symbol</th>
<th>PL6</th>
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<td>188</td>
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<td>MCN3</td>
<td>0.194</td>
<td>0.820</td>
<td>188</td>
</tr>
<tr>
<td>SCN16 to SCN20</td>
<td>MCN4</td>
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<td>0.850</td>
<td>245</td>
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<td>MCN4</td>
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<td>0.850</td>
<td>244</td>
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<tr>
<td>SCN21 to C25+</td>
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<td>SCN21 to C25+</td>
<td>MCN5</td>
<td>0.053</td>
<td>0.883</td>
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</tr>
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</table>
3. Analyse experimentally the wellstream compositional data range to between C_{25s} and C_{30s} and input into the software (e.g., WINPROP, PVTi, etc.).

4. If the available experimental compositional is lower than this range, then extend the plus fraction using the gamma distribution function (Whitson, 1983). (This option is available in the software).

5. If experimental specific gravity and molecular weight of the SCN groups (obtained by True Boiling Point analysis) are not available then select this data from charts published by Katz and Firoozabadi (1978). (This option is available in the software).

6. Lump from C_7 to the last fraction into MCN groups by selecting the Whitson (1980) lumping scheme.

7. Determine the EOS parameters P_c, T_c and \omega for the MCN groups and the plus fractions by selecting the correlations published by Kesler and Lee (1976) and Lee and Kesler (1980).

8. Select the default values for \Omega_a (0.4572) and \Omega_b (0.0778) (taken from WINPROP, 2011).

9. Select the correlation published by Oellrich et al (1981) for obtaining BIC between methane and the heavy fractions. Select an exponent value of 1.2 as a starting value for tuning the Hydrocarbon Interaction Coefficient Exponent (HICE), n (WINPROP, 2011).

10. Select the tuning parameters BIC between methane and the heavy fractions, \Omega_a and \Omega_b for methane and \Omega_a and \Omega_b for the plus fraction.

11. Set weight factors of 40 for dew point pressure 1 for liquid volume and 10 for Z factor.

12. Set the upper and lower bounds for the tuning parameters to allow a change of ±20 % of the test values so as to ensure that they remain physically reasonable (WINPROP, 2011). For HICE, set the bounds (between 0.0 and 1.8) which are the limits appropriate for typical petroleum fluids (WINPROP, 2011).

5. Conclusions

From the study, the following conclusions are made:

1. Compositions beyond SCN24 give best prediction of CVD data by the tuned EOS studied.

2. The volume shift parameter should be included with the parameters BIC, P_c, T_c and \omega when tuning the Peng-Robinson (1976) EOS. A weight factor of 10 as suggested by (Danesh, 1998) should be applied to liquid volume.

3. The volume shift parameter (VSP) should not be included with the parameters BIC and the \Omega s when tuning the Peng-Robinson (1976) EOS. A weight factor of 1 should be applied to liquid volume and 10 to gas compressibility factor.

4. Peng-Robinson (1976) EOS predictions of CVD data with the tuning parameters BIC and the \Omega s were more accurate than with the tuning parameters BIC, P_c, T_c, \omega and VSP.

5. The accuracy obtained with Whitson’s (1980) lumping scheme shows that it can be applied in compositional simulation studies and complex forms of lumping and algorithms to select the best lumping schemes that are not required.

6. This study demonstrated the consistency in tuning the Peng-Robinson (1976) EOS with one regression step which avoids wastage of time spent in trial and error when tuning.

Acknowledgements

The authors would like to thank the Campus Research and Publication Fund Committee of The University of the West Indies for providing the financial support for this Research Project.

Appendix 1: Peng-Robinson (1976) EOS

The Peng-Robinson (1976) EOS, which when expressed in terms of molar volume has the form:

\[ P = \frac{RT}{(V-b)} - \frac{a}{[V(V+b)+b(V-b)]} \]

where P is the pressure and temperature of the system, R is the molar gas constant, a and b are constants characterising the molecular properties of the individual components in a mixture. Parameter b corrects for the volume of the molecules which is considered negligible for an ideal gas. Parameter a corrects for attractive forces between molecules and the walls of the containing vessel (Peng-Robinson, 1976; Ahmed, 1989) and parameter \alpha (Soave, 1972) was included to make parameter a temperature dependent.

By imposing the classical Van der Waals’ (1967) critical point constraints on Equation A1, (Peng-Robinson, 1976) expressions for a and b can be obtained as follows:

\[ a = \Omega_a R^2T_c^2 / P_c \text{ and } b = \Omega_b RT_c / P_c \]

where P_c and T_c are the critical pressure and temperature of the component. Expressing equation 1 (Peng-Robinson, 1976) in terms of gas compressibility factor z_c (Soave, 1972; Martin, 1979), the coefficients \Omega_a and \Omega_b take the values of 0.45724 and 0.07780 at the critical point.

Peng-Robinson (1976) adopted Soave’s (1972) approach for calculating the parameter \alpha, where theacentric factor \omega was introduced to characterise the non-sphericity of component molecules for improved predictions by:

\[ \alpha = (1+(0.480+1.574\omega-0.176\omega^2)(1-T/T_c)^{1.5})^{0.5} \]

where (T_c = T / T_c)
and included a binary interaction coefficient (BIC) $k_{ij}$ (Soave, 1972) into the attractive pressure term, to model intermolecular interaction in a mixture by empirical adjustment, as follows:

$$\begin{align*}
(a)_{m} &= \sum_{i} \sum_{j} x_{i} x_{j} (a_{i} a_{j} a_{ij}^{0.5}) k_{ij}
\end{align*}$$

(A4)

$$b_{m} = \sum_{i} x_{i} b_{i}
$$

(A5)

where $x_{i}$ and $x_{j}$ represent the mole fractions of components $i$ and $j$ in a liquid mixture. These are replaced by $y_{i}$ and $y_{j}$ for a gas mixture. BICs are dependent on differences in molecular sizes in a mixture and are determined from correlations or by minimising the difference between predicted and experimental saturation pressure for binary systems (Danesh, 1998).

Theoretically, EOS has an inherent deficiency in predicting liquid density away from the critical point. A correction parameter $c$ (Jhaveri and Youn gren, 1984) can be applied to the Peng-Robinson (1976) EOS to correct for liquid and vapor volumes as follows:

$$V_{L,corr} = V_{L} - \sum_{i} (x_{i} c_{i})
$$

(A6)

$$V_{V,corr} = V_{V} - \sum_{i} (y_{i} c_{i})
$$

(A7)

where $x_{i}$ and $y_{i}$ are the mole fractions of component $i$ in the liquid and gas phase, $V_{L}$ and $V_{V}$ are the volumes of the liquid and gas phase as calculated by the Peng-Robinson (1976) EOS, $V_{L,corr}$ and $V_{V,corr}$ are the corrected volumes of the liquid and gas phase and $c_{i}$ is the volume correction parameter defined by:

$$c_{i} = V_{SP, b_{i}}
$$

(A8)

where $V_{SP, b_{i}} = 1 - d / (M)\alpha$

In Equation A8, $b_{i}$ is the Peng-Robinson (1976) molecular parameter for component $i$, defined in Equation A2. $V_{SP, b_{i}}$ is a dimensionless parameter of component $i$, called the volume shift parameter. Values of $V_{SP, b_{i}}$ for the components methane to pentane have been documented by Ahmed (1989). For the Single Carbon Number ( SCN) groups (greater than pentanes) and the plus fraction, $V_{SP, b_{i}}$ is determined from the molecular weight $M$ of each component (Table A1) and the positive correlation coefficients $d$ and $e$ (Jhaveri and Youngren, 1984). Where no experimental data is available for calculating $d$ and $e$, Jhaveri and Youngren (1984) recommended adjusting coefficient $d$ to match the $C_{7+}$ density and to use a value of 0.2051 for the power coefficient $e$.

References:


Hosein, R. (2004), Phase Behaviour of Trinidad Gas Condensates, Ph.D. Thesis (unpublished), The University of The West Indies, St Augustine, Trinidad.


Table A1: Compositions and Properties for Trinidad Samples PL1 to PL6

<table>
<thead>
<tr>
<th>Component</th>
<th>Symbol</th>
<th>PL1 Mole %</th>
<th>PL2 Mole %</th>
<th>PL3 Mole %</th>
<th>PL4 Mole %</th>
<th>PL5 Mole %</th>
<th>PL6 Mole %</th>
<th>Specific Gravity</th>
<th>Molecular Wt., g/mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>CO2</td>
<td>0.241</td>
<td>0.874</td>
<td>0.350</td>
<td>0.323</td>
<td>0.284</td>
<td>0.585</td>
<td>0.817</td>
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<tr>
<td>Nitrogen</td>
<td>N2</td>
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<td>0.058</td>
<td>0.077</td>
<td>0.088</td>
<td>0.077</td>
<td>0.088</td>
<td>0.809</td>
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<td>91.640</td>
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<td>1.826</td>
<td>3.333</td>
<td>1.83</td>
<td>3.521</td>
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<td>Propane</td>
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<td>1.313</td>
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<td>iso-Butane</td>
<td>i-C4</td>
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<td>0.471</td>
<td>0.383</td>
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<td>0.346</td>
<td>0.298</td>
<td>0.563</td>
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<td>n-Butane</td>
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<td>iso-Pentane</td>
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<td>0.241</td>
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<td>0.624</td>
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<tr>
<td>n-Pentane</td>
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<tr>
<td>Undecanes</td>
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<td>0.196</td>
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<td>C13</td>
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<td>0.146</td>
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<td>0.119</td>
<td>0.074</td>
<td>0.077</td>
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<td>0.052</td>
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<tr>
<td>Heptadecanes</td>
<td>C17</td>
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<td>0.065</td>
<td>0.059</td>
<td>0.045</td>
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<td>0.847</td>
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<td>Octadecanes</td>
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<td>0.052</td>
<td>0.049</td>
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<td>Nonadecanes</td>
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<td>0.021</td>
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<table>
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<tr>
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<th>PL1</th>
<th>PL2</th>
<th>PL3</th>
<th>PL4</th>
<th>PL5</th>
<th>PL6</th>
</tr>
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<tbody>
<tr>
<td>Mole %</td>
<td>C7+</td>
<td>3.924</td>
<td>2.753</td>
<td>2.919</td>
<td>2.268</td>
<td>2.122</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>γ7+</td>
<td>0.8031</td>
<td>0.8004</td>
<td>0.7939</td>
<td>0.7967</td>
<td>0.7918</td>
</tr>
<tr>
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<td>157</td>
<td>150</td>
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<tr>
<td>Mole %</td>
<td>C11+</td>
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<td>1.12</td>
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<td>0.778</td>
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<td>0.8407</td>
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<tr>
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<td>222</td>
<td>213</td>
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<td>211</td>
</tr>
<tr>
<td>Mole %</td>
<td>C15+</td>
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<td>0.572</td>
<td>0.525</td>
<td>0.449</td>
<td>0.368</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>γ15+</td>
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<td>0.8576</td>
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</tr>
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<td>266</td>
<td>261</td>
<td>263</td>
</tr>
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<td>Mole %</td>
<td>C20+</td>
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<td>0.240</td>
<td>0.187</td>
<td>0.149</td>
<td>0.134</td>
</tr>
<tr>
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<td>Molecular Wt.</td>
<td>M20+</td>
<td>326</td>
<td>345</td>
<td>332</td>
<td>321</td>
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</tr>
</tbody>
</table>

Sources: Data taken from Hosein (2004), Katz and Firoozabadi (1978)
Table A2: Constant Volume Depletion Data (CVD) for Trinidad Gas Condensate Samples PL1 to PL6 measured at Reservoir Temperature

<table>
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<tr>
<th>Pressure psia</th>
<th>Prod. Gas (Cum.), %</th>
<th>Liquid Vol. (Cum.), %</th>
<th>Gas Comp. Factor, Z</th>
<th>Pressure psia</th>
<th>Prod. Gas (Cum.), %</th>
<th>Liquid Vol. (Cum.), %</th>
<th>Gas Comp. Factor, Z</th>
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<td>5814.7</td>
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Source: Data taken from Hosein (2004)


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Mechanical Behaviour of Cold Deformed and Solution Heat-treated Alumina Reinforced AA 6063 Metal Matrix Composites

Kenneth Kanayo Alaneme

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Abstract: The mechanical behaviour of cold deformed and solution heat-treated aluminium alloy (6063)- alumina particulate composites was investigated. AA 6063-Al2O3 particulate composites having 6, 9, and 12 volume percent of Al2O3 were produced using two-step stir casting process. The composites were cold rolled to 20 and 35% deformation before solution heat-treating at 550°C for 1 hour cooling rapidly in water. Density measurements were used as a basis of evaluating the percent porosity of the composites; while tensile properties and fracture toughness were utilised to study the mechanical behaviour. It was discovered that the cold rolling and solution heat-treating processes resulted in remarkable reduction in porosity levels in the AA 6063/Al2O3p composites (≤ 2.8 % porosity). A good uniform distribution of the alumina particulates in the matrix of the AA 6063 was also produced. The tensile strength and yield strength increased with increase in alumina volume percent and degree of cold rolling. The strain to fracture and fracture toughness decreased with increasing volume percent alumina but improved with increase in the degree of cold deformation.

Keywords: stir casting; AA 6063- Al2O3; cold rolling; mechanical behaviour; porosity; solution heat-treatment

1. Introduction

Metal Matrix Composites (MMCs) have become an important class of engineering materials because of the unique properties and higher performance efficiencies they offer over traditional metals and alloys utilised for the same applications (Matthews and Rawlings, 1994; Miracle, 2005). Some of the remarkable property combinations of MMCs are high specific strength and stiffness, better high temperature strength and stability in comparison to its base alloy, low thermal coefficient of expansion, and satisfactory levels of corrosion resistance (Ray, 1993; Zhou and Xu, 1997; Hashim et al., 1999).

Among MMCs, Aluminium based metal matrix composites have been the most developed and utilised for a wide range of engineering applications (Surappa, 2003). Some of its areas of applications are in the design of components/accessories for use in aerospace technology, defence, electronic heat sinks, solar panel substrates and antenna reflectors, automotive drive shaft fins, explosion engine components, sports among others (Chawla et al., 2009; Veeresh Kumar et al., 2010).

There have been sustained efforts by materials researchers to develop AMCs using simple, cost-effective, and technically efficient processing techniques. A two-step stir casting has been explored to develop AMCs with very encouraging results with regards lowered porosity levels (less than 4 %) achieved. However, in the as-cast or solution heat-treated conditions some of the AMCs do not possess sufficient toughness and mechanical strength even when porosity levels are satisfactory (Alaneme and Bodunrin, 2011).

Recently, there has been interest to develop AMCs based on the use of Aluminium alloy 6063 (Khalifa and Mahmoud, 2009; Alaneme and Bodunrin, 2011; Alaneme and Aluko, 2012a). AA 6063 are conventionally applied for the design of medium strength window and door profiles and other architectural design works (Polmear, 2006). The choice of AA 6063 is informed by its local availability and lower cost of processing.

The present research work presented here is aimed at improving the mechanical properties of AA 6063 – alumina composites by adopting cold rolling and solution heat-treat in combination as a secondary processing stage in the production of the AMCs.

2. Materials

100 percent chemically pure alumina (Al2O3) particles having particle size of 28µm and Aluminium alloy 6063 (AA 6063) which served as the matrix; were utilised for the production of the composite. The composition of the AA 6063 is shown in Table 1.

| Table 1: Chemical Composition of the Aluminium Alloy 6063 |
|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| Si                      | Fe                      | Cu                      | Mn                      | Mg                      |
| 0.45                    | 0.22                    | 0.02                    | 0.03                    | 0.50                    |
| Zn                      | Cr                      | Ti                      | Al                      |
| 0.02                    | 0.03                    | 0.02                    | Bal.                    |

3. Methods
3.1 Production of Composites by Stir Casting

Charge calculations were utilised to determine the quantities of Aluminium (6063) alloy and alumina (Al₂O₃) particles required to produce composites having 6, 9, and 12 volume percent alumina. The alumina particles were initially preheated at a temperature of 250°C for 5-10 minutes to help improve wet-ability with the AA 6063 alloy. The AA 6063 ingots were charged into a gas-fired crucible furnace and heated to a temperature of 750°C ± 30°C (above the liquidus temperature of the alloy) and the liquid alloy was then allowed to cool in the furnace to a semi solid state at a temperature of about 600°C.

The preheated alumina was added at this temperature and stirring of the slurry was performed manually for 5-10 minutes. The composite slurry was then superheated to 720°C and a second stirring performed using a mechanical stirrer. The stirring operation was performed at a speed of 300rpm for 10 minutes to help improve the distribution of the alumina particles in the molten AA 6063. The molten composite was then cast into prepared sand moulds. Unreinforced AA 6063 was also prepared by casting for control experimentation.

3.2 Cold Rolling and Solution Heat-treatment Processing

The cast composites of 6, 9, and 12 volume percent alumina along with the unreinforced alloy; was subjected to cold deformation using a miniature cold rolling machine. The composites were rolled to 20 and 35 % degrees of deformation using the round orifice of the cold rolling machine before solution heat-treating the samples at 550°C for 1 hour, then cooling rapidly in water. The sample designations for the different temper conditions (as-cast, 20% and 35% cold rolled and solution heat-treated conditions) are presented in Table 2.

3.3 Density Measurement

The density measurements were carried out to determine the porosity levels of the composites produced. This was achieved by comparing the experimental and theoretical densities of each volume percent Al₂O₃ reinforced composite (both for the as-cast and the cold deformed – solution heat-treated conditions). The experimental density of the samples was evaluated by weighing the test samples using a high precision electronic weighing balance with a tolerance of 0.1mg. The measured weights in each case were divided by the volume of the respective samples. The theoretical density was evaluated by using the rule of mixtures given by:

\[ \rho_{\text{EX}} = \rho_{\text{AA6063}} \times (1 - \phi) + \rho_{\text{Al2O3}} \times \phi \] .......................... (2.1)

Where, \(\rho_{\text{EX}}\) = Experimental Density (g/cm³), \(\rho_{\text{AA6063}}\) = Density of AA 6063, \(\rho_{\text{Al2O3}}\) = Density of Al₂O₃, and \(\phi\) = Volume fraction of Al₂O₃.

The percent porosity of the composites was evaluated using the relations:

\[ \% \text{Porosity} = \left\{ \left( \rho_{\text{f}} - \rho_{\text{EX}} \right) \div \rho_{\text{f}} \right\} \times 100 \] .......................... (2.2)

Where, \(\rho_{\text{f}}\) = Theoretical Density (g/cm³), \(\rho_{\text{EX}}\) = Experimental Density (g/cm³)

3.4 Tensile Properties Determination

Room temperature uniaxial tension tests were performed on round tensile samples machined from the unreinforced alloy and the composites with dimensions of 6 mm diameter and 30 mm gauge length. The testing was performed using an instron universal testing machine operated at a constant cross head speed of 1mm/s; and the procedure adopted was in conformity with ASTM E8M - 91 standards (ASTM, 1991). Three repeat tests were performed for each test condition to guarantee reliability of the data generated. The tensile properties evaluated from the stress-strain curves developed from the tension test are - the ultimate tensile strength (\(\sigma_u\)), the 0.2% offset yield strength (\(\sigma_y\)), and the strain to fracture (\(\varepsilon_f\)).

3.5 Fracture Toughness, \(K_{IC}\)

Circumferential notch tensile (CNT) specimens were prepared for the evaluation of fracture toughness in accordance with Alaneme (2011). The CNT specimens were machined with gauge length of 30mm, specimen diameter of 6mm (D), notch diameter of 4.5mm (d) and notch angle of 60°. The specimens were then subjected to tensile loading to fracture using an instron universal testing machine. The fracture load (\(P_f\)) obtained from the CNT specimens’ load – extension plots were used to evaluate the fracture toughness using the empirical relations by Dieter (1988):

\[ K_{IC} = \frac{P_f}{(D) \sqrt{d}} \left[ 1.72(D/d) - 1.27 \right] \] .......................... (2.3)

Where, \(D\) and \(d\) are respectively the specimen diameter and the diameter of the notched section. The validity of the fracture toughness values was evaluated using the relations in accordance with Nath and Das (2006):

\[ D \geq \frac{(K_{IC}/\sigma_y)^2}{2} \] .......................... (2.4)
A minimum of two repeat tests were performed for each treatment condition and the results obtained were taken to be highly consistent if the difference between measured values for a given treatment condition is not more than 2%.

3.6 Microstructure
The microstructural investigation was performed using a Zeiss Metallurgical Microscope. The specimens for the optical microscopy were polished using a series of emery papers of grit sizes ranging from 500-1,500 μm; while fine polishing was performed using polycrystalline diamond suspension of particle sizes ranging from 10-0.5 μm with ethanol solvent. The specimens were etched using 1HNO₃: 1HCl solution by swabbing before microstructural examination was performed.

3.2 Percent Porosity
The results of the percent porosity of the as-cast, 20% and 35% cold rolled and solution heat-treated AA 6063/Al₂O₃p composites are presented in Figure 2. It is observed that the as-cast AA 6063/Al₂O₃p composites had the highest porosity levels (1.85-3.78%) in comparison with the 20% cold rolled and solution heat-treated composites (1.05-2.8 %) and the 35% cold rolled and solution heat-treated composites (0.74-2.0 %). For all temper conditions, it is observed that the percent porosities are less than 4 % which is reported as the maximum permissible porosity level in cast metal matrix composites (Kok, 2005; Prabu et al., 2006; Alaneme and Aluko, 2012a). The percent porosity can be observed to increase with increase in volume percent alumina and decreases with the degree of cold deformation. This is an indication that the cold rolling and solution heat-treating process helps in improving the quality of the cast composites by reducing the percent porosity.

The reduced porosity of the cold deformed and solution heat-treated composites is attributed to the cold rolling process which compresses the composites thereby aiding the collapse of voids, micro-cracks and vacancies in the composite making it more compact and denser (Huda, 2009).

4. Results and Discussion
4.1 Microstructure
Figure 1 shows optical photomicrographs for the 9 and 12 volume percent Al₂O₃ reinforced AA 6063 composites in the as-cast and 35% cold rolled and solution heat-treated conditions (which are selected as representative microstructures for all the temper conditions for the composites produced). It is observed that the Al₂O₃ particulates are well dispersed in the cold rolled and solution heat-treated condition in comparison to the as-cast condition. This is a clear indicator that the cold rolling and solution heat-treatment processes helped in achieving a homogeneous distribution of the particulates and reduced particle clusters in the composites produced.
composites increases with increase in volume percent alumina and extent of cold deformation. The cold rolling and solution heat-treatment helps in achieving a refined and homogeneous structure by removing voids and micro-voids and also helps in redistributing the particulates and second phase particles resulting in considerable elimination of particle clusters and segregation (Shahani and Clyne, 2003; Huda, 2009). The elimination of a considerable amount of defects in the composite by the cold rolling and solution heat-treatment process helps in enhancing the strain hardening capacity of the composites (Shahani and Clyne, 2003).

The variation of fracture toughness of the composites with increase in $\text{Al}_2\text{O}_3$ volume percent is presented in Figure 5.

The results were taken to be reliable because the requirement for nominal plain strain condition was met with the specimen diameter of 6mm when the relation $D \geq (K_{1C}/\sigma_y)^2$ (Nath and Das, 2006) was utilised to test for the validity of the $K_{1C}$ values evaluated from the CNT testing. The fracture toughness was observed to decrease with increase in volume percent of $\text{Al}_2\text{O}_3$ but improves with degree of cold deformation before solution heat-treatment. The fracture micro-mechanism in particulate reinforced MMCs has been reported to be due to particulate cracking, interfacial cracking or particle debonding (Alaneme and Aluko, 2012b; Ranjbaran, 2010). The reduced porosity and considerable elimination of particle clusters in the composites is responsible for the slight improvement in the fracture toughness of the composites. Generally, the fracture toughness values obtained for the composites were found to be comparable to that of Al matrix composites processed under similar conditions (Milan and Bowen, 2004).

5. Conclusion

It was discovered that the cold deformation and solution heat-treating processes resulted in remarkably reduced porosity levels in the AA 6063/$\text{Al}_2\text{O}_3_p$ composites ($\leq 2.8$ %porosity). A good uniform distribution of the alumina particulates in the matrix of the AA 6063 was also produced. The tensile strength and yield strength increased with increase in alumina volume percent and degree of cold deformation. The strain to fracture and fracture toughness decreased with increasing volume percent alumina but improved with increase in the degree of cold deformation.

References:

Alaneme, K. K. (2012), “Influence of Thermo-mechanical Treatment on the Tensile Behaviour and CNT evaluated Fracture Toughness of Borax premixed $\text{SiC}_p$ reinforced

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A Three-Stack Mechanical Sieve Shaker for Determining Aggregate Size Distribution of Soils

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Abstract: The design, construction and testing of a soil dry sieving apparatus is described. It could be used to effectively determine the aggregate size distribution curves of three dry soil samples simultaneously. The design required that a means be developed to agitate soil samples placed on three stacks of sieves. Both vertical and slight outward movements of the soils in the sieve nest were obtained in this particular design. Three soils were used to test this equipment using the operating parameters of three vibration frequencies and three sieving times. Best sieving of the three soils was obtained at 1.75 Hz frequency for a sieving time of 15 minutes. Results obtained at this best operating condition were then compared to those obtained from an existing commercial mechanical sieve shaker at the same 15 minutes sieving time. The results showed that the constructed three-sieve shaker performed very well in comparison with the commercial shaker; in addition it was quieter and easier to operate. The major advantage of the constructed three-sieve mechanical sieve shaker is that three stacks of sieves are incorporated into the design. This decreases by almost three times, the normal time required for aggregate size analysis using the existing commercial shakers, which all utilise single sieve stacks.

Keywords: Soil, sieve, stack, shaker

1. Introduction

The size distribution of dry soil aggregates is of importance to many professionals involved in soils research. It provides information on the soil’s physical structure (bulk density, consistency), and its susceptibility to wind and water erosion (Chepil, 1942; Wischmeier and Smith, 1978). It also determines the soil’s suitability for specific crops based on its capacity for water, nutrient and heat, infiltration and aeration. Adequate knowledge of aggregate size-distribution and texture may be used to inform interested parties of appropriate land-use. Better retention walls can be built and residences and road works can be more suitably located in mountainous areas. Aggregate-size distribution also affects soil compaction since soils with uneven aggregate size distribution are expected to pack more closely than those with uniform distribution (Brady and Weil, 1999).

Aggregate size distribution of soils is usually determined by either wet sieving (Kemper and Koch, 1966) or dry sieving (Chepil and Bisal, 1943). While wet sieving is used to determine the proportion of stable aggregates resistant to water disruption during rainfall (Ekwue, 1990), dry sieving is utilised mainly to relate aggregate sizes to soil erosion by wind (Chepil, 1942).

Determining aggregate size distribution of a soil by hand is a very laborious process; consequently, mechanical shakers have been developed to simplify the process. There is no universal agreement on the method to be used in dry sieving soils. Over the years, different methods of sieving have been developed and have proven extremely effective in determining the aggregate size distribution of soils. Six major types of commercial mechanical sieve shakers were identified by Eccles and Ekwue (2008). Mechanical sieve shakers utilise different types and modes of agitating forces to sieve the soil. These are discussed in Section 2. One distinct disadvantage of the present commercial mechanical shakers is that they are very expensive due to complicated operation process and only sieve one stack of soil at a time. This makes the analysis of several soil samples a very time consuming process. To enhance the effectiveness of these machines, Eccles and Ekwue (2008) produced a mechanical sieve shaker that could sieve two soil samples at a time.

The current design examines a way of making mechanical sieving even less time consuming by sieving three soil samples simultaneously by using three stacks of sieves. The cost of the machine is also decreased by simplifying its design as well as its principle of operation.
2. Existing Commercial Mechanical Shakers

To establish the necessary design specifications for the sieving machine, a product research was conducted which involved an analysis of ten commercial sieving machines (see Table 1). Data were collected on the size of the machines, the form and amplitude of their sieving motion, the size of the sieve stack, the maximum number of sieves possible and the measuring range/timing interval. This information was used for comparison and bench marking to assist in determining the product performance requirements. The main drawback in all the products except the two-stack mechanical sieve shaker was that each device could only process one batch of soil at a time. This meant that if many samples of soil were to be tested, then the process could be very time-consuming.

In determining the requirements of the constructed mechanical shaker, some of the more important design parameters were the maximum number of soil samples able to be sieved at a time, the time required to complete the process, the size of the device, the cost of the device and the effectiveness of the design. Consequently, the design should:

- Allow for an adjustable number of sieve pans in the stack in order to vary the number of samples that can be sieved at a time.
- Be relatively compact and inexpensive.
- Reduce the time taken to sieve a given number of samples of soil.
- Be as effective as the commercially available mechanical sieve shakers.

The device described in the following section satisfies these requirements.

3. Description of the Constructed Three-Stack Mechanical Sieve Shaker

3.1 Construction

Figure 1 shows the construction of the sieving machine. There is the rigid immobile load-bearing frame which consists of the base frame, the front support, the vertical support, the U support and the top bar to which a three arm sub-assembly is welded.

<table>
<thead>
<tr>
<th>Product Name</th>
<th>Sieve Diameters</th>
<th>Max sieve Height</th>
<th>Sieving Motion</th>
<th>Max. Batch</th>
<th>Max Number of sieves</th>
<th>Max Sieve Mass</th>
<th>Amplitude of Motion</th>
<th>Measuring Range/Interval Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retsch AS 450</td>
<td>400/450 mm</td>
<td>963 mm</td>
<td>6 electromagnetically driven springs give rise to a throwing motion with angular momentum – 3D motion</td>
<td>25 kg</td>
<td>13/9</td>
<td>50 kg</td>
<td>0.2 – 2.2 mm</td>
<td>25 μm – 125 mm/10 - 99s</td>
</tr>
<tr>
<td>Ro-Tap Sieve Shaker RX-29</td>
<td>200 mm</td>
<td>Full height 65/50 mm each half height 40/25 mm each</td>
<td>Electromagnetic drive performing 278 oscillations per minute as well as 150 taps per minute</td>
<td>5 kg</td>
<td>6/13</td>
<td>*NS</td>
<td>NS</td>
<td>45 μm - 25 mm/20 -30 min</td>
</tr>
<tr>
<td>Fritsch</td>
<td>200 mm</td>
<td>550 mm Both full and height sieves</td>
<td>Electromagnetic drive – vertical; line frequency 60 Hz</td>
<td>2 kg</td>
<td>10/16</td>
<td>3 kg</td>
<td>0-3 mm</td>
<td>25 – 63 mm/3 – 20 min</td>
</tr>
<tr>
<td>Meinzer II Sieve Shaker</td>
<td>200 mm</td>
<td>Both full and half height sieves</td>
<td>Electromagnetic drive – vertical and horizontal motion; line frequency 60 Hz</td>
<td>NS</td>
<td>8/15</td>
<td>NS</td>
<td>NS</td>
<td>60 min timer</td>
</tr>
<tr>
<td>Gilson SS-15 Sieve Shaker</td>
<td>8 inch</td>
<td>Both full and height sieves</td>
<td>Back and forth lateral motion is combined with up and down and tilting motions to cause test material to travel in an orbit on the sieve surfaces. Delivered by ¼ hp motor</td>
<td>NS</td>
<td>6 / 13</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Analysette 3-Spartan Digital Sieve Shaker</td>
<td>NS</td>
<td>NS</td>
<td>Vertical oscillation generated by an electromagnetic drive.</td>
<td>5 kg</td>
<td>Up to 10</td>
<td>NS</td>
<td>NS</td>
<td>20 μm - 25 mm/10 - 20 min</td>
</tr>
<tr>
<td>DuraShake Sieving Machine</td>
<td>NS</td>
<td>Full height 304.8 mm each Half height 203.2 mm ea</td>
<td>Rotates soil at an angle and taps it using a series of nylon blocks, all controlled by a 1/3 hp motor.</td>
<td>NS</td>
<td>5/9</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Two-Stack Mechanical Sieve Shaker</td>
<td>200 mm</td>
<td>Vertical &amp; Horizontal Motion, together with a tapping motion generated by an arm-follower approach. Two sieve-stacks are shaken simultaneously.</td>
<td>NS</td>
<td>8</td>
<td>NS</td>
<td>32 mm in each direction</td>
<td>75 μm – 4.75 mm/10 min</td>
<td></td>
</tr>
</tbody>
</table>

Remarks: NS - not specified in product literature.
3. Description of the Constructed Three-Stack Mechanical Sieve Shaker

3.1 Construction

Figure 1 shows the construction of the sieving machine. There is the rigid immobile load-bearing frame which consists of the base frame, the front support, the vertical support, the U support and the top bar to which a three arm sub-assembly is welded. There are 3 pins rigidly attached to the base frame which support a big ring. This ring has a series of evenly spaced “cam-like” elevations with a symmetric parabolic profile of height 25.4 mm and length 133.4 mm.

Energy is transferred from a ¼ hp motor to the driven shaft via a linked belt and pulley system. The driven shaft has a disc keyed to it; the disc rigidly supports three soil sieve stack bases beneath each of which is a roller follower. The keyway prevents relative rotation of the disc with respect to the shaft; however, it allows for appreciable axial motion of the disc. The soil sieve bases support a stack guide with adjustable stack caps.

Each soil sieving stack consists of 7 sieves ranging from sieve number 4 (4.75 mm diameter mesh) to sieve number 200 (0.075 mm diameter mesh). The largest sieve opening (4.75 mm) was placed on top and the receiving pan on the bottom. The top bar of each stack guide has a pin which passes freely through a central bore of each arm sub-assembly. A compression spring is placed between the top bar of each stack guide and the underside of its associated arm sub-assembly.

![Figure 1. Views of the three-stack mechanical soil sieve shaker](image)

3.2 Principle of Operation

A sample of soil to be sieved is placed in the top bowl of each stack. The stack is then loaded into the stack holder and constrained by the stack cap. Next, the motor is turned on. Energy is transferred to the shaft with the attached disc – soil sieve bases assembly. As the bases rotate, their roller followers move around the large ring. When they encounter the elevations, they force the sieve to be subjected to a reciprocating up-down motion. Two key components which facilitate this motion are the keyway between the shaft and the disc (which allows axial motion) and the holder’s top support pin which can freely move within the bore of its arm sub-assembly. The reciprocating vertical motion provides the sieving action; once the frequency is high enough, contact is lost between the soil and the sieve chamber. This agitating
action allows the smaller loose particles to pass through the sieve into a lower sieve.

If the system is shaken long enough, eventually only soil particles which are larger than the mesh size (or very close to it) will be left in each sieve. The increase in compression of the spring as the stack moves over the elevations generates forces which push the soil stack holder down, and is transmitted to the sieve stacks thereby increasing the sieving action. Since there are three elevations on the big ring, the frequency of the reciprocating motion is three times the rate of rotation rate of the driven shaft.

One main advantage of this design is the compactness of the machine. It does not take up much space and the user can place and remove stacks very easily from the holders.

4. Testing of the Constructed Three-Stack Mechanical Soil Sieve Shaker

4.1 Purpose of the tests

Tests were conducted to investigate the best vibration frequency and time of sieving for the constructed three-stack machine. The frequency of vibration of the mechanical shaker in Hz was described as the number of events (up-down motions of the soil stack) within a given time frame. The machine design requires a judicious use of the frequency. If the frequency is too low, the particles will not be agitated enough to ensure the finer soil passes through the mesh. However, if the frequency is too large, the shaking effect may become undesirable when trying to determine in-situ soil composition. Since the vibration frequency that could yield the best sieving of the soil for the constructed machine was not known a priori, the machine was tested at output speeds of 25, 35 and 45 rpm which corresponded to frequencies of 1.25, 1.75 and 2.25 Hz, respectively.

The time required for sieving is also an important design parameter. Whitby (1959) indicated that within a given sieve of the stack, the process may be considered to consist of two different sieving regimes. When the sieving begins, there are many particles within the chamber which are much less than the sieve size. During the first seconds within the first sieving regime, as the soil is agitated, most of the smaller particles fall through the sieve. After this time, regime two of the sieving occurs; most of the soil particles within each sieve are larger than the sieve mesh size. Any particles remaining which are theoretically able to pass through the mesh are very close to the mesh size.

The cumulative distribution of the soil passing through the sieve follows the pattern of log normal distribution (Hagen et al., 1987). The sieving process must be long enough so that each sieve could reach its individual regime two process. However, there is also an upper limit on the time taken for processing after which the clods of soil begin to break up; this is undesirable when trying to determine the in-situ soil composition. Sieving times of 5, 15 and 15 minutes were utilised so as to determine the best time for sieving.

The machine was tested for repeatability of results; consequently, each soil sample was sieved or tested three times. Tests were also carried out to compare the accuracy of the device in relation to existing commercial mechanical sieve shakers. The results obtained by using the constructed three-stack mechanical sieve shaker to obtain the aggregate size distribution by dry sieving were compared to those obtained using an existing commercial mechanical shaker: the RoTap machine (Laval Lab Incorporated, 2005). The RoTap sieving machine utilises a rotary motion and a slight tapping at the top of the sieve set every second. The machine holds one set of soil sieves at a time.

4.2 Procedure for soil testing

Three common agricultural soil samples in Trinidad (see Table 2) were utilised for the tests: Piarco sandy loam, Maracas clay loam and Talparo clay. The mechanical analysis of the soils was carried out using the hydrometer method (Lambe, 1951) while the organic matter contents were determined using the Walkley and Black method (1943). The soil materials to be tested were first air-dried. Soil aggregates or lumps were then thoroughly broken up with fingers or with a mortar and pestle. The aim here was to make sure that the soil sample consisted of individual aggregates. 2000 grams of soil were used for each test.

The actual tests for the three-stack mechanical sieve shaker were a full factorial experiment involving the three soils at three vibration frequencies (1.25 Hz, 1.75 Hz and 2.25 Hz) with operating times of 5, 10 and 15 mins. Each test was replicated three times to give a total of 81 tests.

<table>
<thead>
<tr>
<th>Soil Series</th>
<th>Classification*</th>
<th>Organic Matter Content (%)</th>
<th>Aggregate Size Distribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sand (0.06-2 mm)</td>
</tr>
<tr>
<td>Piarco sandy loam</td>
<td>Aquoxic Tropudults</td>
<td>1.7**</td>
<td>64.9</td>
</tr>
<tr>
<td>Maracas clay loam</td>
<td>Orthoxic Tropudults</td>
<td>4.7</td>
<td>44.7</td>
</tr>
<tr>
<td>Talparo clay</td>
<td>Aquentic Chromuderts</td>
<td>2.7</td>
<td>25.4</td>
</tr>
</tbody>
</table>

Remarks: * - Classification according to the Soil Taxonomy System (Soil Survey Staff, 1999).
** - All values are means of three replicates.
The soil samples were then transferred into the top of a stack of sieves arranged in opening sizes of sieves (0.075 to 4.75 mm diameter) and put on the shaker, where they were sieved for 5, 10 or 15 min each. When the oscillation of the mechanical shaker was completed, the sieve stacks were removed and carefully disassembled. The mass of soil retained in each sieve was determined by weighing and the percentage of soil that passed through each sieve was determined. The full mechanical sieving process and the analysis of results were fully described by Lambe (1951) and Eccles and Ekwue (2008).

5. Results and Discussion

5.1 Operation

During the testing, it was observed that the constructed three-stack mechanical shaker produced a smooth oscillating motion; there was no apparent noise generation and little or no visible vibration. Removal and placement of the sieves was easier using the new machine than the RoTap mechanical shaker. There was also greater flexibility in the adjustment of its operating parameters.

5.2 Repeatability of results

The results were examined for repeatability. Table 3 shows the results obtained when three different tests were conducted on Talparo soil with the three-stack sieve at 1.25 Hz frequency for 5 minutes of operation. It shows that the distribution curves obtained over the three tests were close to each other. In fact, the minimum coefficient of determination between any two of the soil distribution data was 0.999 (perfect fits correspond to a coefficient of determination of 1). Hence the machine had repeatable results.

In addition, the percentages of soil that passed through each sieve size were determined and these were used to plot the aggregate size distribution curves for each soil sample. Figure 2 shows the distribution curves for each of the three soil types when the sieving machine was operated at 1.75 Hz for 15 minutes. The distribution curves obtained for different combinations of frequency and sieving time are similar in format. Three basic soil parameters (effective size, uniformity coefficient and coefficient of gradation) were obtained from the distribution curves and used to classify the sieved soil samples. Table 4 details the values of these basic soil parameters of the soils tested with the three-stack mechanical sieve shaker for the three experimental factors of soil type, vibration frequency and sieving time.

The effective size of a soil is defined as the diameter in the aggregate size distribution curve corresponding to 10% finer and is denoted as D_{10} (Das, 2002). Since all the D_{10} values are less than 0.25 mm, all the soil samples were sieved to their fine states by the constructed three-stack mechanical sieve shaker. The uniformity coefficient (UC) is a measure of the aggregate size range. It is the ratio of the diameter corresponding to 60% finer (D_{60}) to the effective size (Das, 2002). A high uniformity coefficient indicates that the fine and coarse materials are more thoroughly blended i.e. the sample is more non-uniform.

All the sieved Talparo clay soil samples can be classified as non-uniform since they all have uniformity coefficients greater than 5. For the other two soils, some of the UC values were more than 5 showing non-uniformity. The coefficient of gradation is the measure of the shape of the aggregate size curve (Das, 2002) and is defined as shown in Table 4. Since many of the sieved samples had the coefficient of gradation within the range of 1 to 3, they are classified as well-graded. This means that the smaller aggregates will pack between the larger ones. There is fairly even distribution of the proportions of all the different aggregate sizes.

Table 3. Repeatability of results from the three-stack sieving machine for the three tests on Talparo clay soil at 1.25 Hz and 5 minutes sieving time

<table>
<thead>
<tr>
<th>Sieve Number</th>
<th>Diameter of Sieve (mm)</th>
<th>Mass of soil retained and percentage of soil passing each sieve</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Test 1 Mass Retained (g) % Passing</td>
</tr>
<tr>
<td>4</td>
<td>4.750</td>
<td>2.9 98.83</td>
</tr>
<tr>
<td>6</td>
<td>3.350</td>
<td>46.5 80.05</td>
</tr>
<tr>
<td>10</td>
<td>2.000</td>
<td>79.9 47.78</td>
</tr>
<tr>
<td>50</td>
<td>0.300</td>
<td>50.9 27.22</td>
</tr>
<tr>
<td>70</td>
<td>0.212</td>
<td>28.6 15.67</td>
</tr>
<tr>
<td>140</td>
<td>0.106</td>
<td>21.6 6.95</td>
</tr>
<tr>
<td>200</td>
<td>0.075</td>
<td>16.1 0.44</td>
</tr>
<tr>
<td>PAN</td>
<td>1.1</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Figure 2. Aggregate-size distribution of the three soils for a 1.75 Hz vibration frequency of the three-stack mechanical soil sieve shaker compared with the RoTap shaker. Sieving time was 15 minutes.

Table 4. Values of some aggregate size parameters of the soils obtained by the constructed three-stack mechanical soil sieve shaker operating at different vibration frequencies and sieving times

<table>
<thead>
<tr>
<th>Soil Type and Moisture Content</th>
<th>Sieving Time</th>
<th>D_{10}</th>
<th>D_{30}</th>
<th>D_{60}</th>
<th>Cu</th>
<th>Coefficient of gradation, Cz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piarco sandy loam</td>
<td>5</td>
<td>0.07</td>
<td>0.14</td>
<td>0.30</td>
<td>4.29</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.06</td>
<td>0.13</td>
<td>0.29</td>
<td>4.83</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.04</td>
<td>0.11</td>
<td>0.26</td>
<td>6.50</td>
<td>1.16</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.04</td>
<td>0.11</td>
<td>0.27</td>
<td>6.75</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.05</td>
<td>0.12</td>
<td>0.28</td>
<td>5.60</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.04</td>
<td>0.11</td>
<td>0.26</td>
<td>6.50</td>
<td>1.16</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.07</td>
<td>0.13</td>
<td>0.28</td>
<td>4.00</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.06</td>
<td>0.12</td>
<td>0.27</td>
<td>4.50</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.04</td>
<td>0.11</td>
<td>0.27</td>
<td>6.75</td>
<td>1.12</td>
</tr>
<tr>
<td>Maracas clay loam</td>
<td>5</td>
<td>0.10</td>
<td>0.18</td>
<td>0.42</td>
<td>420</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.09</td>
<td>0.15</td>
<td>0.38</td>
<td>4.22</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.07</td>
<td>0.13</td>
<td>0.36</td>
<td>5.14</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.07</td>
<td>0.14</td>
<td>0.36</td>
<td>5.14</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.05</td>
<td>0.13</td>
<td>0.34</td>
<td>6.80</td>
<td>0.99</td>
</tr>
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<td></td>
<td>15</td>
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<td>0.14</td>
<td>0.36</td>
<td>7.20</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.09</td>
<td>0.16</td>
<td>0.43</td>
<td>4.78</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.07</td>
<td>0.13</td>
<td>0.38</td>
<td>5.43</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.06</td>
<td>0.13</td>
<td>0.38</td>
<td>6.33</td>
<td>0.74</td>
</tr>
<tr>
<td>Talparo clay</td>
<td>5</td>
<td>0.12</td>
<td>0.57</td>
<td>1.54</td>
<td>12.83</td>
<td>1.76</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.14</td>
<td>0.61</td>
<td>1.60</td>
<td>11.43</td>
<td>1.66</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.10</td>
<td>0.54</td>
<td>1.51</td>
<td>15.10</td>
<td>1.93</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.12</td>
<td>0.60</td>
<td>1.59</td>
<td>13.25</td>
<td>1.89</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.10</td>
<td>0.52</td>
<td>1.45</td>
<td>14.50</td>
<td>1.86</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.07</td>
<td>0.50</td>
<td>1.45</td>
<td>20.71</td>
<td>2.46</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.14</td>
<td>0.53</td>
<td>1.44</td>
<td>10.29</td>
<td>1.39</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.12</td>
<td>0.55</td>
<td>1.52</td>
<td>12.67</td>
<td>1.66</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.11</td>
<td>0.54</td>
<td>1.50</td>
<td>13.64</td>
<td>1.77</td>
</tr>
</tbody>
</table>

Remarks: a Diameter (mm) of the aggregate to which 10% is finer is defined as effective size
b Uniformity coefficient, Cu = D_{60}/D_{10}
c Coefficient of gradation, Cz = D_{30}^{2}/(D_{60} x D_{10})

5.3 Effect of the experimental factors on soil aggregate size parameters

Table 5 shows the mean values of the basic soil parameters for the three experimental factors. Results showed that mean effective size, D_{10}, D_{30} and D_{60} increased with increasing clay content in the soils. This is expected because soils with greater levels of clay content are expected to be more aggregated. Values of D_{10}, D_{30} and D_{60} were lowest for the 1.75 Hz frequency of vibration and 15 mins sieving time in all cases. This
shows that at this frequency and time of sieving, the soil stacks were well shaken and the best sieving of soils took place in the constructed shaker. In Table 5, it shows that the uniformity coefficient and the coefficient of gradation were the highest for this combination. This further confirms that of all the combinations tested, a 1.25 Hz frequency and a 15 min sieving time gives the best operating condition for the constructed three stack mechanical sieve shaker. At the operating frequency of 1.25 Hz, it was observed that the soil and the stacks raised and fell as a unit. In other words, the operating frequency was too low to ensure that the acceleration of the reciprocating motion exceeded that due to gravity. The contact between the soil and the sieve was therefore lost. Consequently, there was no effective agitating action which was required to sieve the soil aggregates. The opposite was true for the 2.25 Hz. The speed of the three stacks at this frequency pushed the soil outwards and gave it insufficient time to pass through the sieves.

5.4 Accuracy of the constructed sieving machine

Results obtained by operating the three-stack soil mechanical sieve shaker at 1.75 Hz and 15 minutes sieving time (the most efficient combination of operating conditions as described above) were compared with those obtained from using the RoTap sieve shaker at 15 minutes. The distribution curves produced (Figure 2) were very close to each other. This closeness was verified by the coefficients of determination obtained between the average soil distribution data used to plot the curves for Piarco sandy loam, the Talparo clay soil and the Maracas clay loam. In each case, the results were compared with those from the RoTap machine, which were 0.996, 0.996 and 0.974, respectively. This indicates that the machine is able to produce results with a high degree of accuracy.

It was seen that the RoTap Shaker generally produced curves that were slightly higher than those obtained using the constructed shaker in the case of Maracas clay loam and the Piarco sandy loam. As a higher curve usually indicates a better sieving action, this means that the RoTap shaker gave slightly better results for these two soils. This meant that the constructed shaker probably needed a more vigorous shaking action to produce equivalent or better results than the RoTap shaker. There are several parameters which could be varied to determine the effect on this shaking action. The first two (the height and length of the parabolic elevations on the big ring) have not been examined in this article. However, each of these has an effect on the vertical component of the acceleration of the sieve stack which in turn affects the agitation properties. The frequency of events could also be adjusted. This could be done by varying the number of elevations on the big ring or by adjusting the motor speed. However, as discussed in the principle of operation, it is important to realise that if the frequency is too high the sieving action can be compromised. Finally, the sieving time could be adjusted to obtain better results.

The basic soil parameters obtained from the distribution curves in Figure 2 are shown in Table 6. The constructed three-stack mechanical shaker gave similar classification results to the RoTap sieve shaker although the D_{10}, D_{50}, D_{60} obtained for the RoTap sieve shaker were a bit lower than those for the constructed three-stack sieve shaker indicating a better sieving action in the former. In general, the RoTap mechanical shaker also gave higher uniformity coefficients and coefficients of gradation indicating that the soils were better sieved and had higher chances of being non-uniform. The values obtained from the two mechanical sieving machines were, however, enough to classify all the three soils tested in similar categories. The results obtained by the constructed shaker at present are, therefore, greater than satisfactory in determining the aggregate size distribution of any soil.

Table 5. Mean values of D_{10}, D_{50}, D_{60}, uniformity and coefficient of gradation for the three experimental factors of the three-stack mechanical soil sieve shaker

<table>
<thead>
<tr>
<th>Factor Level</th>
<th>Mean D_{10} (mm)</th>
<th>Mean D_{50} (mm)</th>
<th>Mean D_{60} (mm)</th>
<th>Mean Uniformity Coefficient</th>
<th>Mean Coefficient of Gradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Type</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piarco (Sandy Loam)</td>
<td>0.05</td>
<td>0.12</td>
<td>0.27</td>
<td>5.40</td>
<td>1.07</td>
</tr>
<tr>
<td>Maracas (Clay Loam)</td>
<td>0.07</td>
<td>0.14</td>
<td>0.38</td>
<td>5.43</td>
<td>0.74</td>
</tr>
<tr>
<td>Talparo clay</td>
<td>0.11</td>
<td>0.55</td>
<td>1.50</td>
<td>13.64</td>
<td>1.83</td>
</tr>
<tr>
<td>Frequency of Vibration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.25 Hz</td>
<td>0.09</td>
<td>0.28</td>
<td>0.73</td>
<td>8.11</td>
<td>1.19</td>
</tr>
<tr>
<td>1.75 Hz</td>
<td>0.06</td>
<td>0.26</td>
<td>0.70</td>
<td>11.67</td>
<td>1.61</td>
</tr>
<tr>
<td>2.25 Hz</td>
<td>0.08</td>
<td>0.27</td>
<td>0.72</td>
<td>9.00</td>
<td>1.27</td>
</tr>
<tr>
<td>Time of Sieving</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 minutes</td>
<td>0.09</td>
<td>0.28</td>
<td>0.73</td>
<td>8.11</td>
<td>1.19</td>
</tr>
<tr>
<td>10 minutes</td>
<td>0.08</td>
<td>0.27</td>
<td>0.72</td>
<td>9.00</td>
<td>1.27</td>
</tr>
<tr>
<td>15 minutes</td>
<td>0.06</td>
<td>0.26</td>
<td>0.71</td>
<td>11.83</td>
<td>1.59</td>
</tr>
</tbody>
</table>

Remarks: *Mean values for each factor were obtained by averaging the measured values over the levels of the other two experimental factors. Number of experimental points is 81 representing a factorial experiment with 3 soil types, 3 frequencies of vibration, 3 times of sieving and 3 replications.
6. Conclusions
The following could be concluded from the study:

- The constructed three-stack mechanical sieve shaker was found to be user friendly and easy to operate.
- It was well suited for laboratory work.
- The machine was found to be sufficient to sieve and effectively or correctly grade or classify the three soil samples investigated.
- It produced consistent results for each type of soil examined.
- The best sieving action was obtained with a frequency of vibration of 1.75 Hz and a 15-minute sieving time.
- The constructed shaker performed with a degree of accuracy just below that of the RoTap machine.
- The total cost of the device was approximately TT$6,200.00 (approximately US$1,000.00), just over 40% of the cost of a commercial grade single stack shaker.

Future work will be carried out on the machine to determine the most appropriate sieving time, “cam-like” elevation parameters and frequency of operation.

References:


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Table 6. Mean values of D10, D30, D60, uniformity coefficient and coefficient of gradation for the three-stack mechanical soil sieve shaker operating at 1.75 Hz vibration frequency and for the RoTap shaker at 15 mins sieving time

<table>
<thead>
<tr>
<th>Soil and Mechanical Shaker Types</th>
<th>D10   (mm)</th>
<th>D30   (mm)</th>
<th>D60   (mm)</th>
<th>Uniformity Coefficient</th>
<th>Coefficient of Gradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piarco sandy loam:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Three-stack shaker</td>
<td>0.04</td>
<td>0.11</td>
<td>0.26</td>
<td>6.50</td>
<td>1.16</td>
</tr>
<tr>
<td>RoTap shaker</td>
<td>0.03</td>
<td>0.10</td>
<td>0.25</td>
<td>8.00</td>
<td>1.33</td>
</tr>
<tr>
<td>Maracas clay loam:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Three-stack shaker</td>
<td>0.05</td>
<td>0.14</td>
<td>0.36</td>
<td>7.20</td>
<td>1.09</td>
</tr>
<tr>
<td>RoTap shaker</td>
<td>0.03</td>
<td>0.11</td>
<td>0.27</td>
<td>9.00</td>
<td>1.49</td>
</tr>
<tr>
<td>Talparo clay:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Three-stack shaker</td>
<td>0.07</td>
<td>0.50</td>
<td>1.45</td>
<td>20.71</td>
<td>2.46</td>
</tr>
<tr>
<td>RoTap shaker</td>
<td>0.06</td>
<td>0.44</td>
<td>1.36</td>
<td>22.67</td>
<td>2.37</td>
</tr>
</tbody>
</table>

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Effect of Cooking Time on Select Physical and Mechanical Properties of Dried Pigeon pea (Cajanus cajan)

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Abstract: Improvement of the processing technology of pigeon pea requires accurate information on the physical and mechanical properties of the legume, as affected by primary processing. This study investigated the effect of cooking duration on select physical and mechanical properties of dried pigeon pea. The physical properties measured were length, breadth, thickness, mass, density, sphericity, aspect ratio and moisture content, using standard methods. Force at yield, break and peak; energy to yield, break and peak; deformation at break and peak; and Young modulus, were the mechanical properties measured using a Testometric device. Cooking times (1, 2, 3, 4, 5, and 6 hours) at 100 °C was used. Means of 250 replicates were calculated and data analysed using ANOVA and regression. The length, breadth, and thickness of the samples varied from 6.29 ± 0.39 to 8.18 ± 0.61 mm, 5.59 ± 0.30 to 6.95 ± 0.84 mm and 4.18 ± 0.29 to 5.40 ± 0.61 mm, respectively. With increase in cooking time, mass, sphericity, aspect ratio, density and moisture content, ranged from 0.11 to 0.20 g, 71.1 ± 7.8 to 100.0 ± 9.4, 63.7 ± 4.1 to 88.0 ± 6.5, 0.91 ± 0.1 to 1.47 ± 0.3 kg/cm³, and 8 ± 0.7 to 66 ± 4.1%, respectively. Effect of cooking time on mechanical properties of force, energy, deformation, and Young modulus was significant at 5% level of significance. Polynomial models were fit to express the relationships. Coefficient of determination R² of the equations ranged from 0.7 to 1.0. Cooking duration of two hours was adequate to soften the pea, using strength as the criterion. The data generated can be applied in the design of processing equipment.

Keywords: Pigeon pea, cooking, duration, physical properties, mechanical properties

1. Introduction

Pigeon pea (Cajanus cajan), also known as red gram, Congo pea, gungo pea, no eye pea, dhal, gandul, gandure, frijol de árbol, pois cajan, and otili, occurs in several varieties. The legume grows on a wide range of well-drained soils, from sands to clays, over sedimentary, igneous, and metamorphic parent materials. The pea tolerates pH values from 4.5 to 8.4, and some varieties tolerate 6 to 12 mmhos/cm of salinity (Francis, 2011). However, the varieties are sensitive to water-logging. The pigeon pea is an important legume in developing tropical countries. As an excellent source of protein, the seeds (and sometimes the pods) are consumed as a vegetable, as a flour additive to other foods, in soups, and with rice (CNCPP, 2002). Pigeon pea forms root nodules in association with Rhizobium sp. bacteria, and it is capable of fixing 41 to 280 kg/ha of nitrogen (APS, 2002). Pigeon pea contains moisture (10.1%), protein (18.8%), fat (1.9%), carbohydrates (53.0%), fiber (6.6%), and ash (3.8%) (Saxena, 2008).

Additionally, mineral and trace elements found in the legume are calcium (120 mg/g), magnesium (122 mg/g), copper (1.3 mg/g), iron (mg/g) and zinc (2.3 mg/g); vitamins are carotene (469.0 mg/g), thiamin (0.3 mg/g), riboflavin (0.3 mg/g), niacin (3.0 mg/g), and ascorbic acid (25.0 mg/g). In spite of the nutritional potential of this crop, it is still classified as underutilised.

Processing of pigeon pea involves de-podding, cleaning, cooking, drying, and milling. The seed of the pigeon pea is enclosed in a hard, tough, and relatively thick coat that has a semi-permeable membrane. Movement of water through the mesocarp is restricted, because the adhesive force that binds the mesocarp to the seed is relatively high (Ghadge, Shewalkar and Wankhede, 2008). Therefore, cooking is necessary to soften the firmly attached seed coat for easy dehulling. The traditional boiling time of 8-10 hrs discourages use. A reported method of reducing cooking time is soaking in water for six hours, then boiling in 6% Na₂CO₃ (Achi, 2005). The cooking time is reduced to 3 hours, and de-hulling efficiency is increased to 78%.

Engineering properties of crops are essential parameters in utilisation, in the development of processing methods, and in equipment design (Akinoso and Raji, 2011). These properties include rheological, thermal, optical, electrical, physical, and mechanical. Mohsenin (1986) described various methods for measuring crushing force. These methods include the use of automatic recording universal hardness of testing machines. Studies in engineering properties of
agricultural products include Koya and Faborode (2005) on palm nuts, Chemperek and Rydzak (2006) on maize grain, and Altuntas and Yildiz (2007) on faba bean. Others are Andrejko et al. (2008) on pea seed, Kibar and Ozturk (2008) on soybean, and Fathollahzadeh and Rajabipour (2008) on barberry. Altuntas and Sekeroglu (2008) and Tavakoli et al. (2009) have reported on chicken egg and wheat straw, respectively. Researchers have clearly shown that engineering properties of biomaterial significantly depend on moisture content, maturity, shape, and size of crop.

Improvement of the processing technology of pigeon pea requires accurate information on the physical and mechanical properties of the legume, as affected by primary processing. Studies on cooking time reduction, without compromising food value, will provide info that can be used to reduce energy demand, encourage interest in its consumption, thereby increasing its utilisation. Therefore, the objective of this study was to determine the effect of water-cooking duration on select physical and mechanical properties of dried pigeon pea.

2. Materials and Methods

2.1 Samples Preparation

Dried pigeon peas (32C variety) of 8% moisture content (wet basis) were collected from the Institute of Agricultural Research and Training Ibadan, Nigeria was used for the study. A 1 x 6 factorial design was used (Christopher, 1983). Cooking times were 1, 2, 3, 4, 5 and 6 hours, at atmospheric pressure (760-mmHg ≈ 1 bar) and boiling temperature (100 oC). The peas were cooked in distilled water using 3mm thick stainless steel container placed on a kerosene stove. At attainment of the desired heating duration, the container was removed, the water drained after which the peas were cooled to ambient temperature (29oC) in desiccators containing silica gel as the desiccant.

2.2 Physical Properties

Physical properties of size (length, breadth, thickness), mass, shape, and density of the samples, were determined using standard methods (Akinoso and Raji, 2011). Length, breadth, and thickness were determined using a venier calliper with 0.01mm accuracy (Cappera precision, China). A digital weighing balance (Scout™ Pro OHaus model SPU401) of accuracy ± 0.001g was used for mass measurement. Means of 250 cooked seeds, randomly selected, were calculated and recorded. The sphericity and aspect ratio were determined according to Mohsenin (1986), using Equations 1 and 2, respectively.

\[ SI = \left(\frac{\alpha \beta \delta}{\alpha} \right)^{1/2} \times 100 \]  
\[ RA = \left(\frac{\beta}{\alpha} \right) \times 100 \]

Where SI was sphericity (%), was aspect ratio (%), and α, β, δ were length, breadth and thickness in mm respectively.

2.3 Moisture Content

The relationship between mass and volume was applied for bulk density calculation. Moisture content of the peas was determined using the ASABE (2008) standard method for oilseed. Three samples (15g each) were placed in an oven set at 130 oC for 6 hrs. The samples were then cooled to ambient temperature (29oC) in desiccators containing silica gel as the desiccant. The dried samples were weighed using a digital weighing balance (Scout™ Pro OHaus model SPU401). The difference in weight before and after drying was calculated as moisture loss. The ratio of moisture loss to weight of wet material in percentage was recorded as moisture content, wet basis (% wb).

2.4 Mechanical Properties

Mechanical properties viz: force at break, deformation at break, energy to break, force at peak, deformation at peak, energy to peak, force at yield, energy to yield, and Young modulus, were determined using a Testometric AX Type DBBTCL 2500 kg (Rochdale, England). These tests were conducted using the method of Akinoso and Raji (2011). The seed samples were placed between the compression plates of the testing equipment. Each pea was compressed at a constant deformation rate 10.00mm/min., and readings were made using a data logger. The procedure was repeated in 250 replicates. Mean values were recorded. Data obtained were subjected to ANOVA and regression analysis at p< 0.05.

3. Results and Discussion

3.1 Size Characteristics

Length, breadth, and thickness of pigeon peas were 6.29 ± 0.39 to 8.19 ± 0.60 mm, 5.59 ± 0.30 to 6.95 ± 0.65 mm and 4.18 ± 0.29 to 5.37 ± 0.51 mm, respectively. As cooking time increased, ANOVA of the data showed significant (p<0.05) impact of cooking on the three spatial dimensions. Graphical illustration of the relationship is given in Figure 1.

![Figure 1. Plot of cooking time against size](image-url)
Effect of cooking duration on breadth was fit to fifth order polynomial, while third order polynomial best represented the behaviour of length and thickness to treatment. Seed size is important in the design and selection of equipment for primary processing of separation (Akinoso and Raji, 2011). The significant effect of cooking duration on size may be related to moisture absorption capability of the legume. Sobukola and Onwuka (2011) reported similar observations when locust beans were soaked in water.

3.2 Mass
Mean mass recorded after 0, 1, 2, 3, 4, 5 and 6 h of cooking were 0.11± 0.00 g, 0.195 ± 0.00 g, 0.190 ± 0.00 g, 0.20 ± 0.00 g, 0.185 ± 0.00 g, 0.185 ± 0.00 g, and 0.185 ± 0.00 g, respectively. The observed differences were not significant when subjected to ANOVA at 5% level of significance. Weight of crops is one of the major determinants in the selection of handling equipment (Mijinyawa, 2007). Therefore, the results suggest that consideration for mass in the design of handling equipment such as conveyors, could be generalised regardless of cooking duration. Illustration of the relationship is shown in Figure 2. Third order polynomial equation was suitable to express the cooking effect on seed mass.

3.3 Density
Bulk density of the samples ranged from 0.91 ± 0.01 to 1.47 ± 0.3 kg/m³. Bulk density has practical application in determining separation of product from undesirable materials (Fellows, 2000). Cleaning is an important unit operation in food processing (Fellows, 2000). The sink and floating method is applicable for these samples because none of their densities was equal to density of water (1g/cm³) (see Figure 2).

3.4 Moisture Content
Cooking of the seed increased its moisture content from 8.10 ± 1.03 to 66.0 ± 2.7 % (wet basis). Significant effect (p<0.05) of cooking on moisture content of the crop was recorded. Figure 3 shows the effect of increased cooking time on moisture content of the peas. Second order polynomial fits well for the curve. Increased moisture content with increase in cooking time was an expected phenomenon. Pigeon pea is a biomaterial that has affinity for water. However, it should be noted that water absorption causes re-distribution of chemicals within the peas (Ihekoronye and Ngoddy, 1985). Effect of variation in composition of a food on thermal properties has been reported (Choi and Okos, 1987). Design of an efficient boiler is a function of thermal properties (Barbosa-Canovas et al., 2006).

3.5 Shape
The mean sphericity and aspect ratio of the samples varied from 71.1 ±7.8 to 100.0 ± 9.4 %, and 63.7 ± 4.1 to 88.2 ± 6.5 %, respectively. Effect of cooking was significant (p < 0.05) on both properties. As seen in Figure 4, both sphericity and aspect ratio were well fit into sixth order polynomial model. Coefficients of determination of the models were 1.
sphericity and aspect ratio is an indication of the seeds tending to a spherical shape. These properties are useful in the design of dehulling equipment (Mohsenin, 1986). Dehulling is one of the unit operations in pigeon pea processing (Ghadge, et al., 2008).

3.6 Force

The minimum and maximum forces at yield, break, and peak of the samples were 173.4 ± 25.3 to 2.8 ± 1.3 N, 529.7 ± 37.3 to 12.3 ± 1.7 N and 529.7 ± 37.2 to 11.9 ± 1.7 N, respectively. Applied forces decreased with increased cooking time (see Figure 5). Third order polynomial model fit illustrates the relationship between the forces and cooking duration. No significant (p> 0.05) difference was recorded between the forces at break and peak. Generally, the treatment effect was significant on compressive forces. Deformation increased with increased cooking time (see Figure 6).

![Figure 5](image1.png)

**Figure 5.** Plot of force against cooking duration

![Figure 6](image2.png)

**Figure 6.** Plot of deformation against cooking duration

It is to be noted that the increment was not linear. The relationship is best described by fourth order polynomial. Cooking effect was significant on deformation at 5% level of significance. Strength of food is used in determining cooking quality objectively (Ihekorkonye and Ngoddy, 1985). The results on mechanical properties agreed with Olayanju et al. (2006) who reported significant influence of hypothermal treatment on physico-chemical properties of soybean. Andrejko et al., (2008) reported similarly on dried peas subjected to thermal processing using infrared radiation. Noticeable difference between yield and break point indicated high ductility of the crop. The possibility of moisture uptake influence on the ductility should not be ignored. Low tensile strength of the crop might be responsible for complete fracture at break point (Barbosa-Canovas et al., 2006).

3.7 Energy and Young Modulus

Energy to yield, break, and peak ranged from 0.00019 ± 0.000 to 0.09 ± 0.00 J, 0.0039 ± 0.000 to 0.566 ± 0.03 J, and 0.0039 ± 0.000 to 0.566 ± 0.03 J, respectively. Energy to break and peak was the same. Nevertheless, significance difference was noticed between energy to yield and others. Cooking duration on energy consumption or usage is shown in Figure 7. Results indicate that decreased energy is required for compression with increased cooking time.

![Figure 7](image3.png)

**Figure 7.** Plot of energy against cooking duration

As seen in Figures 5 and 7, two (2) hours of cooking were adequate to soften the peas. Therefore, results suggest that during traditional cooking of 8 – 10 hrs, reactions occur that affect the physico-elastic and strength of pigeon pea. Young modulus of pigeon pea after 0, 1, 2, 3, 4, 5, and 6 hours of cooking were 546.30 ± 42.77 N/mm², 21.09 ± 2.41 N/mm², 7.98 ± 1.81 N/mm², 8.97 ± 1.61 N/mm², 6.91 ±1.33 N/mm², 13.69 ±4.08 N/mm² and 12.08 ± 4.3 N/mm², respectively. Cooking hours influenced Young modulus of the crop significantly at 5% level of significance. Polynomial model was fit to illustrate the relationship (see Figure 8). Young modulus is a material property that describes its stiffness (Barbosa-Canovas et al., 2006).
4. Conclusions

Cooking time influenced size, shape, and moisture absorption capacity of dried pigeon pea. Compressive force and deformation of the crop were functions of the cooking duration. Effects of cooking on physical and mechanical properties of pigeon were not linear, thus optimum cooking time is required. Cooking duration of two (2) hours was adequate to soften the pea, using strength as the criterion. Reduction in cooking duration will save energy requirements for the unit operation, thus reducing pigeon pea processing costs. The data generated can be applied in the design of processing equipment. It is recommended that nutritional values of the cooked pigeon pea at two hours should be determined. In addition, thermal properties of the pea should be studied.

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Figure 8. Plot of Young modulus against cooking duration
Department of Food Technology in 2008. He had served dutifully in various administrative capacities within and outside the University. Dr. Akinoso is a member of professional bodies, which include Nigeria Institution of Agricultural Engineers, American Society Agricultural and Biological Engineers, Nigeria Society of Engineers, and Nigerian Institute of Food Science and Technology. His research interest is in Food Engineering in which he has over thirty publications in reputable local and international journals.

Idayat Motunrayo Lasisi hails from Kuta, Osun State Nigeria. She was admitted to Department of Food Technology, University of Ibadan, Nigeria in 2006. She graduated in 2011 with B.Sc. Degree (Honours) in Food Technology.
Some Engineering and Chemical Properties of Cooked Locust Bean Seed (Parkia biglobosa)

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Abstract: This study was conducted to determine effect of cooking duration on some engineering and chemical properties of locust bean seed. The locust bean seed was cooked for 1, 2, 3, 4, 5, and 6 hours. Length, breadth, and thickness of locust bean were 10.38 to 12.52 mm, 8.61 to 10.04 mm and 4.79 to 5.83 mm, respectively. Bulk density ranged from 0.77 to 1.62 g/cm3. Cooking of the bean increased moisture content from 4.4 to 61.4%. Compressive forces required reaching the yield, breaking and peak point of the samples ranged from 10.22 to 211.26 N, 51.70 to 384.39 N, and 51.88 to 385.87 N, respectively. Young modulus decreased with increased cooking time while deformation increased. Cooking has significant influence on chemical properties at 5% level of significance. Thermal conductivity of un-cooked locust bean increased from 0.22 to 0.52 W/mK and specific heat increased from 1.92 to 2.60 kJ/kgK.

Keywords: Locust bean, cooking, physical properties, mechanical properties, proximate composition, thermal properties

1. Introduction
Locust bean (Parkia biglobosa) is used in many food dishes in West Africa. The most important use of locust bean is found in its seeds which are rich in protein, lipids, carbohydrate, vitamin B2 and when fermented are also rich in lysine (Akanfe, Adejumo, Adamade and Bodunde, 2010). Iru the fermented locust bean is a valuable food condiment in Nigeria and other countries of West Africa. Processing of locust bean fruits to food condiment (Iru) involves different unit operations including depodding, cleaning, boiling, dehulling, washing, re-cooking, and fermentation. The method of its processing is still largely traditional and labourious. Cooking of the bean was reported to consume highest proportion of energy and time among the unit operations (Adekeye, 2011).

Engineering properties of crops are essential parameters in utilisation, development of processing methods and design of equipment (Akinoso and Raji, 2011a). Such properties include rheological, thermal, optical, electrical, physical, and mechanical properties. Some published works on engineering properties of agricultural products are Ogunsina, Koya, and Adeosun, (2008) on dika nut, Kibar and Ozturk (2008) on soybean and Tavakoli, Mohtasebi and Jafari, (2009) on wheat straw. Findings from these researches clearly showed that engineering properties of biomaterial significantly depend on treatments.

Production of sufficient food at affordable cost is a challenge in most developing countries. Therefore, there is need to ensure that all potential sources of foods are exploited effectively and utilised industrially. The improvements of technology of processing locust bean require accurate information on properties of the crop as affected by primary processing. Study on effect of cooking duration on engineering properties will form a platform for mechanisation of the process. Therefore, objective of this research work was to determine effect of cooking duration on some engineering properties and proximate composition of cooked locust bean seed.

2. Materials and Methods
2.1 Determination of physical properties
A 1 x 6 factorial design was employed. Six levels of cooking time were 1, 2, 3, 4, 5 and 6 hours. Locus bean seed was cooked at atmospheric pressure (760-mmHg= 1 bar) and boiling temperature (100°C). Physical properties of size, mass, shape and density of the samples were determined using standard methods. Length, breadth, and thickness were measured using venier caliper with 0.01mm accuracy (Cappera precision, China). Digital weighing balance (Scout™ Pro model SPU401) of accuracy ± 0.001g was used for mass. Mean of randomly selected cooked 250 seeds was recorded as obtained data. The sphericity and aspect ratio were determined according to reported method (Mohsenin, 1986). Relationship between mass and volume was applied for bulk density determination.
moisture content of the seeds using standard method for oilseed (ASABE, 2008).

2.2 Determination of mechanical properties
Mechanical properties viz: force at break, deformation at break, energy to break, force at peak, deformation at peak, energy to peak, force at yield, energy to yield and the Young modulus were determined using Testometric AX Type DBBMTC-2 500 kg (Rochdale, England). These tests were carried out using reported method (Akinoso and Raji, 2011a). A unit of locust bean from the samples was placed between the compression plates of the testing equipment. Each seed was compressed at a constant deformation rate 10.00 mm/min., and readings were made using data logger. The procedures were repeated in 250 replicates. Mean values were recorded as data. This was subjected to analysis of variance (ANOVA) and regression analysis at p < 0.05.

2.3 Determination of proximate composition
Cleaned locust beans were cooked for four hours. The cooking was done at atmospheric pressure (760-mmHg≈ 1 bar) and boiling temperature (100°C). Appropriate standard methods were used to analyse the proximate composition (AOAC, 2005). AOAC methods 988.05, 958.06, 2003.06, 942.05, and 967.08 were used for determination of protein, fiber content, fat, ash, and moisture content, respectively. Carbohydrate was calculated as reported by Mc Clement (2010). All the experimental procedures were repeated. The mean of three replicate was recorded as data obtained. This was subjected to analysis of variance (ANOVA) at 5% level of significance.

2.4 Determination of protein content
Protein was determined by Kjedahl procedure using a protein factor of 6.25. A sample of about 1.2g was weighed into a digestion tube and conc. tetraoxosulphate (IV) acid (conc. H2SO4) was added using a dispenser. The tube was placed in a preheated digester at 420°C for about 30 minutes until a clear solution was obtained. The tube was removed from the digester, cooled and diluted with water and placed in the distillation unit. A conical flask containing 25ml of boric acid (indicator) was dispensed in the flask if left there. The fat in the spirit was evaporated to dryness over a soxhlet extraction, which extracts n-hexane from its solution of fat. The fat left behind in the flask was placed in the oven to dry at 105°C for 1½ hours. The round bottom flask was cooled in desiccators and weighed. Percentage of fat in sample was calculated.

2.6 Determination of fiber content
Fiber content of the sample was measured using the enzyme-modified, neutral detergent fiber (NDF) method of analysis. Dried samples whose fat content were extracted using soxhlet extraction were treated with standard NDF procedures up to the point that fiber-containing residues were filtered and washed with water. The filtered residues were incubated with a porcine a – amylose solution at 37°C over night. The residues was filtered after incubation, washed very well, and dried. The NDF was calculated as filtered residual.

2.7 Determination of ash content
Ash content of the samples was determined by putting about 25g of sample in a dish of known weight (W4) and dried in an oven for 4 hours at 105°C. It was removed, cooled in desiccators and weighed (W5). The sample in dish was ash in a muffle furnace at 550°C until white or grey ash resulted. It was cooled and reweighed (W6). The percentage ash content was calculated.

2.8 Determination of moisture content
Moisture content was determined by weighing 25g of sample into cans of known weights (W1). The samples in cans (W1) were placed in an oven for 6 hours at 105°C and then cooled in desiccators and reweighed (W2). Difference in weight was moisture loss.

2.9 Determination of thermal properties
Thermal properties of the samples were determined by fitting experimental data to existing models (Choi and Okos, 1987). Effectiveness of models based on chemical composition of foods for predicting thermo-physical has been reported (Toledo, 2000). Ambient and cooking temperatures were 29°C and 100°C, respectively. Thermal properties determined were thermal conductivity, specific heat, and thermal diffusivity. Thermal conductivity was calculated using (Equations 1 to 16). Specific heat capacity was determined by application of Equations 17 to 23. While equations 24 to 30 were used for thermal diffusivity determination.

\[
k = \sum (k_i X_i) \quad (1)
\]

\[
k_i = k_{w} + k_{f} + k_{e} + k_{a} + k_{d} \quad (2)
\]

\[
X_{w} = X_{f} \rho / \rho_{1} \quad (3)
\]

\[
\rho = \nu (\sum X_i / \rho_i) \quad (4)
\]

\[
k_{w} = 0.57109 + 0.0017625T - 6.7306 \times 10^{-6} T^{2} \quad (5)
\]

\[
k_{f} = 0.1788 + 0.0011958T - 2.7178 \times 10^{-6} T^{2} \quad (6)
\]

\[
k_{e} = 0.1807 - 0.0027604T - 1.7749 \times 10^{-6} T^{2} \quad (7)
\]
Some Engineering and Chemical Properties of Cooked Locust Bean Seed (Parkia biglobosa)

\[ k_c = 0.2014 + 0.0013874T - 4.3312 \times 10^{-6}T^2 \]  
\[ k_p = 0.18331 + 0.0012497T - 3.1683 \times 10^{-6}T^2 \]  
\[ k_a = 0.3296 + 0.001401T - 2.9069 \times 10^{-6}T^2 \]  
\[ \rho_w = 997.18 + 0.0031439T - 0.003754T^2 \]  
\[ \rho_p = 1329.9 - 0.51814T \]  
\[ \rho_f = 925.59 - 0.4175T \]  
\[ \rho_c = 1599.1 - 0.31046T \]  
\[ \rho_{fi} = 1311.5 - 0.36589T \]  
\[ \rho_a = 2423.8 - 0.28063T \]  
\[ \frac{1}{\rho_c} = \frac{1}{\rho_w} + \frac{1}{\rho_p} + \frac{1}{\rho_f} + \frac{1}{\rho_{fi}} + \frac{1}{\rho_a} \]  
\[ C_{pp} = 2.0082 + 1.2089 \times 10^{-3}T - 1.3129 \times 10^{-6}T^2 \]  
\[ C_{pf} = 1.9842 + 1.4733 \times 10^{-3}T - 4.8008 \times 10^{-6}T^2 \]  
\[ C_{pc} = 1.5488 + 1.9625 \times 10^{-3}T - 5.5399 \times 10^{-6}T^2 \]  
\[ C_{pfi} = 1.3459 + 1.3306 \times 10^{-3}T - 4.6509 \times 10^{-6}T^2 \]  
\[ C_{pa} = 1.0926 + 1.8896 \times 10^{-3}T - 3.6817 \times 10^{-6}T^2 \]  
\[ C_{pw} = 4.1762 - 9.0864 \times 10^{-3}T - 5.4731 \times 10^{-6}T^2 \]  
\[ \alpha = \sum (\alpha_i X_i) \]  
\[ \alpha_p = 6.8714 \times 10^{-2} + 4.7578 \times 10^{-4}T - 1.4646 \times 10^{-6}T^2 \]  
\[ \alpha_f = 9.8777 \times 10^{-2} - 1.2569 \times 10^{-4}T + 3.8286 \times 10^{-6}T^2 \]  
\[ \alpha_c = 8.0842 \times 10^{-2} + 5.3052 \times 10^{-4}T - 2.3218 \times 10^{-6}T^2 \]  
\[ \alpha_{fi} = 7.3976 \times 10^{-2} + 3.1902 \times 10^{-4}T - 2.2202 \times 10^{-6}T^2 \]  
\[ \alpha_a = 1.2461 \times 10^{-1} - 3.7321 \times 10^{-4}T - 2.2444 \times 10^{-6}T^2 \]  
\[ \alpha_w = 1.3168 \times 10^{-1} + 6.2477 \times 10^{-4}T - 2.4022 \times 10^{-6}T^2 \]  

Where,  
\( X_i \) is volume fraction of each component,  
\( X_i \) is the mass fraction, %  
\( k \) is thermal conductivity, W/(m.K)  
\( \rho \) is composite density, kg/m³  
\( C_p \) is specific, kJ/kgK  
\( \alpha \) is thermal diffusivity, m²/s  
Subscript i, w, p, f, c, fi and a, indicate for pure component, water, protein, fat, carbohydrate, fiber and ash, respectively.

Results and Discussion

Effects of cooking on physical properties

Length, breadth, and thickness of locust bean were 10.38 ± 0.82 to 12.52 ± 1.33 mm, 8.61 ± 1.20 to 10.04 ± 1.53 mm and 4.79 ± 0.53 to 5.83 ± 0.71 mm, respectively. ANOVA of the data showed significant (p<0.05) impact of cooking only on length. Graphical illustration of the relationship was presented as Figure 1. Effect of cooking duration on length was fit to second order polynomial while third order polynomial best represented the behaviour of breadth and thickness to treatment. Seed size plays important roles in the design and selection of equipment for primary processing of separation (Akinoso and Raji, 2011a).

The significant effect of cooking duration on length may be traced to moisture absorption capability of the crop. Similar observation was reported when locust bean was soaked in water (Sobukola and Onwuka, 2011). Non-significant influence of treatment on breadth and thickness was an indication of low absorption capacity of these sides. There was also possibility of non-uniformity in thickness of the seed coat among the sides, thus encouraging disparity in expansion.

Mean mass recorded after 0, 1, 2, 3, 4, 5 and 6 hours of cooking were 0.25 ± 0.08 g, 0.32 ± 0.03 g, 0.41 ± 0.01 g, 0.49 ± 0.06 g, 0.48 ± 0.08 g, 0.43 ± 0.05 g and 0.47 ± 0.04 g, respectively. The observed differences were not significant when subjected to ANOVA at 5% level of significance. Visual illustration of the relationship was showed as Figure 2. Trend of the plot revealed a polynomial. Fourth order polynomial equation was suitable to express the effect of cooking on the bean mass. The weight of crops is one of the major determinants in the choice of handling equipment (Minjinyawa, 2007). Resultant effect of cooking on breadth and thickness might have influenced the non-significance of cooking on mass. Therefore, this result suggested that consideration for mass in design of handling equipment such as conveyor could be generalised regardless of cooking duration.

![Figure 1. Plot of Size against Cooking Time](image1)

![Figure 2. Plot of Mass and Density against Cooking Time](image2)
moisture content from 4.4 ± 0.9 to 61.4 ± 1.7 % wet basis. Bulk density has practical application in determining separation of product from undesirable materials (Owolarafe et al., 2011). Water flotation method is applicable for these samples because none of their densities was equal to density of water (1g/cm³). Cleaning is an important unit operation in food processing.

Significant effect (p<0.05) of cooking on moisture content of the crop was recorded. Figure 3 shows plot of moisture content versus cooking time. Second order polynomial fitted the curve. Rise in moisture content with increase in cooking duration is an expected phenomenon. Locust bean is a biomaterial, which has affinity for water. However, it should be noted that water caused re-distribution of chemical composition of crop. Effect of variation in composition of a food on thermal properties had been reported (Choi and Okos, 1987). Design of efficient boiler is a function of thermal properties.

The mean sphericity and aspect ratio of the samples varied from 67.83 ± 4.27 to 73.21 ± 5.49 % and 74.99 ± 8.00 to 83.20 ± 9.70 %, respectively. Effect of cooking was significant (p<0.05) on both properties. From Figure 4, aspect ratio fitted well into fourth order polynomial model. However, fitness of sphericity into polynomial model was low with coefficient of determination $R^2$ of 0.556. High sphericity and aspect ratio is an indication of the crop tending to sphere shape. These properties are useful in design of dehulling equipment. Dehulling is one of the unit operations in locust bean processing.

### 3. Effects of cooking on mechanical properties

Compressive forces required to reach the yield, break and peak point of the samples ranged from 10.22 ± 1.03 to 211.26 ± 13.1 N, 51.70 ± 3.38 to 384.39 ± 7.68 N and 51.88 ± 3.37 to 385.87 ± 7.77 N, respectively. Applied forces reduced with an increase in cooking time (see Figure 5). Second order polynomial model was fit to illustrate the relationship between the forces and cooking duration. No significant (p>0.05) difference was recorded between the forces at break and peak. Generally, the treatment effect was significant on compressive forces.

Deformation increased with increase in cooking time (see Figure 6). Cooking effect was significant on deformation at 5% level of significance. Compressive strength of food is used in determining cooking quality objectively.
The obtained results on mechanical properties agreed with Olayanju et al. (2006) who reported significant influence of hydrothermal treatment on physico-chemical properties of soybean. A similar trend was reported on pea seeds subjected to thermal processing using infrared radiation (Andrejko et al., 2008).

Energy to yield, break and peak ranged from $0.01 \pm 0.00$ to $0.15 \pm 0.01$ J, $0.05 \pm 0.00$ to $0.45 \pm 0.09$ J and $0.05 \pm 0.01$ to $0.45 \pm 0.03$ J, respectively. Energy to break and peak was the same. Nevertheless, significance difference was noticed between energy to yield and others. Visual illustration of cooking effect on energy is shown in Figure 7. The plot trend showed a decrease in energy required for compression with increasing cooking time. Young modulus of locust bean after 0, 1, 2, 3, 4, 5, and 6 hours of cooking were $493.27 \pm 29.4$ N/mm$^2$, $244.38 \pm 18.17$ N/mm$^2$, $126.85 \pm 8.11$ N/mm$^2$, $102.62 \pm 6.72$ N/mm$^2$, $54.11 \pm 3.71$ N/mm$^2$, $65.33 \pm 3.28$ and $88.62 \pm 4.73$ N/mm$^2$. Cooking hours influenced the Young modulus of the crop significantly at 5% level of significance.

Polynomial model was fit to illustrate the relationship (see Figure 8). Noticeable difference between yield and break point indicated high ductility of the crop. The possibility of moisture uptake influence on the ductility should not be ignored. Low strength of the crop might be responsible for complete fracture at break point. Polynomial trends of the plots suggested that optimum points exist.

From Figures 5-8, two (2) hours were appropriate. Therefore, there was possibility that during traditional cooking of 8-10 hours, reactions have taken place, which affected physical, chemical, physico-chemical, and strength of locus bean.

4. Proximate composition

Proximate composition of the crop was presented as Table 1. Cooking for four hours had significant influence on all the determined chemical properties at 95% confidence level. Similar observation on wheat cooked at temperatures of 80°C, 100°C, and 120°C was reported (Chukwu et al., 2011).

<table>
<thead>
<tr>
<th>Properties</th>
<th>Un-cooked</th>
<th>Cooked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude protein</td>
<td>29.99±0.10$^a$</td>
<td>18.43±0.06$^b$</td>
</tr>
<tr>
<td>Fat</td>
<td>20.03±0.06$^a$</td>
<td>1.23±0.06$^b$</td>
</tr>
<tr>
<td>Carbohydrate</td>
<td>29.93±0.13$^a$</td>
<td>18.93±0.06$^b$</td>
</tr>
<tr>
<td>Crude fiber</td>
<td>8.71±0.04$^a$</td>
<td>6.50±0.10$^b$</td>
</tr>
<tr>
<td>Ash</td>
<td>5.25±0.01$^a$</td>
<td>2.67±0.15$^b$</td>
</tr>
<tr>
<td>Moisture content</td>
<td>6.09±0.04$^a$</td>
<td>52.23±0.15$^b$</td>
</tr>
</tbody>
</table>

$^a,b$ - Values in the same row with different superscript are significantly different at p < 0.05

4.1 Protein

Crude proteins of un-cooked and cooked locust bean were $29.99 \pm 0.01\%$ to $18.43 \pm 0.06\%$ respectively. Previous work reported decrease in protein content of canavalia cathartica from 32.1 to 28.1% after cooking (Seena et al., 2006). In addition, Baiyeri et al., (2011), reported reduction in protein content of cooked banana from 3.21 to 2.48%. Locust bean has potential of being source of plant protein. Protein quality is a measure of the usefulness of a food protein for the purpose of growth and maintenance of tissue. Thermal denaturation results in coagulation and decreased solubility (Ihekoronye and Ngoddy, 1985)

4.2 Fat

Cooking reduced the fat content of locust bean from $20.03 \pm 0.06\%$ to $1.23 \pm 0.06\%$. Locust bean oil ranged from 19.0 to 22.5% (Akinoso and Raji, 2011b). Wide margin in fat content of cooked and un-cooked locust bean can traced to aqueous extraction of oil from the seed during cooking. Heating fractionated intact oil bodies and rupture cellular structure, thus aided oil extraction.

4.3 Carbohydrate

Carbohydrate content of the raw and cooked locust bean were $29.93 \pm 0.13$ to $18.93 \pm 0.06\%$, respectively. The remarkable reduction in the carbohydrate content is due to hydrolysis of starch to simple sugars during the
cooking period. Hydrophilic groups in carbohydrate molecules caused it to take up moisture in proportion to the relative humidity of the environment (Ihekoronye and Ngoddy, 1985). This characteristic behaviour encouraged moisture uptake and apparent reduction in percentage of carbohydrate.

4.4 Crude fiber
Crude fibers in locust bean were 8.71 ± 0.04% and 6.50 ± 0.15% for raw and cooked samples, respectively. The reduction in fiber content during treatment may be due to dehulling that was noticed during cooking. Hull contains a high portion of the fiber present in the seed (Akinoso and Raji, 2011b). Reduction in crude fiber of locust bean from 11.7 to 4.4 after 6 hours of cooking had been reported (Omafuvbe et al., 2004).

4.5 Ash
The ash content of raw and cooked locust bean were 5.25 ± 0.01% to 2.67 ± 0.15%, respectively. The 5.25% obtained for raw in this study is in consonance with the 5.40% obtained (Omafuvbe et al., 2004) but slightly higher than the 4.24% obtained by (Elemo et al., 2011). Usually there is no appreciable loss of ash in legumes during cooking.

4.6 Moisture content
Cooking locust bean for four hours increased its moisture level from 6.09 ± 0.04% to 52.23 ± 0.15%. Rise in moisture content of locust bean from 8.8% to 56.7% after 6 hours of cooking was reported (Omafuvbe et al., 2004). Moisture uptake of 46.14% was recorded. Significant changes in chemical composition of the crops during cooking are attributed to re-distribution due to this high moisture uptake.

4.7 Thermal conductivity
Cooking for four hours increased thermal conductivity of locust bean by about 100% (see Table 2). Thermal conductivity of the cooked crop close to 0.59 W/mK was reported for tomatoes puree (Choi and Okos, 1987). Bamgboye and Adejumo (2010) reported rise in thermal conductivity of Roselle seed from 1.56 to 1.22 W/mK with increased moisture content of 8.8 to 19.0%, respectively.

<table>
<thead>
<tr>
<th>Table 2. Thermal properties of locust bean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Properties</td>
</tr>
<tr>
<td>Thermal conductivity (W/mK)</td>
</tr>
<tr>
<td>Specific heat (kJ/kgK)</td>
</tr>
<tr>
<td>Thermal diffusivity (m²/s)</td>
</tr>
</tbody>
</table>

- mean of three replicates

4.8 Specific heat
Cooking duration increased specific heat of locust bean from 1.92 to 2.60 kJ/kgK (see Table 2). Changes in this thermal property were significant at 5% level of significance. These values are higher than specific heat capacity of 1.39 kJ/kgK for gua seed (Aviara et al., 2008). Nevertheless, lower than 5.63 kJ/kgK was reported for Roselle seed (Bamgboye and Adejumo, 2010). Specific heat is an essential parameter in design of heat exchanger. The information will be useful in choice of heat transfer medium and processing conditions.

4.9 Thermal diffusivity
Cooking as a treatment significantly influenced thermal diffusivity of locust bean at 5% level of significance (see Table 2). Thermal diffusivity relates to the ability of the material to conduct heat compared to its ability to store heat. Thermal diffusivity is the ratio of thermal conductivity to density and specific heat. Therefore, speed of heat diffusion through a material is also relevant information in processing-time prediction models.

5. Conclusion
Cooking duration influenced size, shape, and moisture absorption capacity of locust bean. Compressive strength and deformation of the crop were functions of the cooking duration. Effects of cooking on physical and mechanical properties of locust beans were not linear, thus an optimum cooking duration is required. Cooking duration of two hours was appropriate using strength as criterion. Cooking of locust bean for four hours changed its chemical and thermal properties significantly. Generated data will be useful in choice of heat transfer medium and processing condition.

References:


Authors’ Biographical Notes:

Rahman Akinoso hails from Abeokuta, Ogun state, Nigeria. He obtained B. Sc. (Honours), M. Sc. and Ph.D. degrees from Department of Agricultural and Environmental Engineering, University of Ibadan, Nigeria. He started his career as researcher in 1999 at Federal Institute of Industrial Research Oshodi (FIRO) Nigeria. He joined the services of University of Ibadan, Nigeria as a Senior Lecturer in Department of Food Technology in 2008. He has served dutifully in various administrative capacities within and outside the University. Dr. Akinoso is a member of professional bodies, which include Nigeria Institution of Agricultural Engineers, American Society Agricultural and Biological Engineers, Nigeria Society of Engineers, and Nigerian Institute of Food Science and Technology. His research interest is in Food Engineering in which he has over thirty publications in reputable local and international journals. Dr. Rahman Akinoso is happily married with children.

Naimat Ebenoluwa El-alawa hails from Ilorin, Kwara State Nigeria. She attended Woodward Nursery and Primary School, Shasha and Lagos State Model College, Igbokuta both in Lagos State, Nigeria for her elementary and secondary education respectively. Naimat was admitted to Department of Food Technology, University of Ibadan, Nigeria in 2006. She graduated in 2011 with B.Sc. Degree (Honours) in Food Technology. As an undergraduate student, she diligently served as National Financial Secretary and Vice president of Nigeria Association of Food Science and Technology in 2009 and 2010, respectively. Presently, she is undergoing mandatory National Youth Service.
Expansion Characteristics of Selected Starchy Crops during Extrusion

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Abstract: In this study, the effect of extrusion process parameters of a locally developed extruder on the expansion of extrudates of the flour and starch of maize and cassava which are grown in Nigeria in large quantity was characterised. These were compared with those of wheat flour which is commonly used for the production of alimentary paste. The parameters considered include feed moisture (30, 40, 50 % d.b.), extruder temperature (40, 70, 100°C) varied by continuous running of the machine, thereby building up the temperature and screw speed (100, 150, 200 rpm). Response Surface Methodology, stepwise regression, correlation and Analysis of Variance were employed to a factorial experiment in completely randomised design. An increase in temperature and screw speed increased transverse expansion. The extrudates' moisture loss is directly proportional with expansion. Increasing feed moisture content caused a decrease in transverse expansion and increase in extrudate moisture content. These starchy crops at low extrusion time are smooth and can be suitable for pasta products. The equations relating extrudates expansion and the independent variables were established to predict the performance of the machine. Generally, the response surface study revealed the range of the extrusion variables for optimum performance. Quadratic coefficients fit the extrusion data very well, better than linear models.

Keywords: Extrusion, cassava, maize, wheat, expansion characteristics

1. Introduction

Food extrusion is a process in which food ingredients are forced to flow, under one or several conditions of mixing, heating and shear, through a die that forms and/or puff-dries the ingredients (Fellows, 2003). Extrusion Technology has gained popularity in the developed nations like United States and Europe by producing a range of products with different shapes, textures, colours, flavours from basic ingredients, thereby increasing the variety of food in the diet (Fellows, 2003). Wheat flour has been widely used in the extrusion industry and the effects of process variables on wheat extrudate properties have been reported (Frame, 1994). Also, Cassava (Manihot esculenta Crantz) and maize (Zea mays) are important starch-rich crops grown in many parts of the world that contributes to economic development and food security, most especially in low income food deficient countries like Nigeria (Asiedu, 1992). Meanwhile, it is obvious that cassava as a crop is not popular for the production of extruded foods. Maize is one of the most common types of starch used for extrusion on which a lot of research work has been done but not in the developing nations where it is grown in large quantity.

The extrusion process operates in a dynamic steady equilibrium where the input variables are balanced with the output (Guy, 2001). For certain applications in the food and packaging industries, starch is extruded to achieve a desired product quality. Extrusion expansion is a complex phenomenon which occurs during high-temperature, low-moisture cooking and is a consequence of several events including starch structural transformations and phase transitions, nucleation, extrudate swell, bubble growth, and bubble collapse, with bubble dynamics dominantly contributing to the expansion phenomenon.

Expansion promotes dehydration and the development of a desirable crispy texture on the final extrudate (Patil et al., 2007). Therefore, expansion related parameters are important to determine the quality of the extruded product. An insight into the expansion characteristics of different starch crops is therefore required for new products development/formulation in developing countries like Nigeria. Such insight would help optimise extrusion processes through better equipment design and applications, and develop new products with desired characteristics that would benefit both the consumers and the industry.

2. Materials and Methods

2.1 Sample preparation

Samples of flour and starch of the two crops under study were sourced and processed from the same varieties grown under the same cultivation practices to give room for basis of comparison of results. Cassava tubers (Manihot esculenta Crantz) TMS 30572, were sourced from experimental plots at the Federal College of Agriculture, Akure and processed into flour and starch.
respectively according to International Starch Institute Standards (2005). The materials were passed through a 300um sieve separately and the proximate analysis and moisture contents (dry basis) of samples were determined as described by AOAC (1995) approved method. White maize, EV8363-SR QPM (breeder seed) was sourced from the International Institute of Tropical Agriculture (IITA), Ibadan and processed into flour and starch respectively as described by Akanbi et al (2003). Hard durum wheat flour (Triticum aestirum) was purchased from Akure main market.

2.2 Extrusion

The extruder used in this study is the dry type. It is made up of three (3) main units namely the feeding unit, the compression and melting unit and the die unit all fabricated using locally available materials. The feeding unit and the compression/melting unit are operated by one electric motor through a gear reducer and belt and pulley transmission system. As a test rig, allowance was given for varying the screw configuration, feed rate, screw speed, die configuration and nozzle. Speed regulation is done by varying the pulley ratios. All parts through which the feed material will pass were made of stainless steel to prevent food contamination and to withstand frictional wear. Figure 1 shows the isometric drawing of the extruder.

As showed in Figure 2, the screw is of single flight, increasing diameter and tapering/decreasing pitch with a compression ratio of 4.5:1 L/D Ratio of 12:1. The diameter of the final portion of the screw is reduced to a cone. This aids in pressure built up, easy conveyance of materials through the die and in reducing wear rate. The length to diameter ratio is 12:1. An electric motor drives the screw through a gear reducer, and the backward thrust of the screw is absorbed by a thrust bearing. The barrel and the screw/die configuration are typical of alimentary food production equipment. The extrudates were extruded as ribbons to be cut with rotary cutter.

2.3 Experimental procedure

Samples were fed into the extruder at a feed rate 10Kg/h. The feeding section of the extruder was maintained at room temperature. The extruder was operated for 30 minutes for each set of condition. Steady state extrusion conditions is assumed to have been reached where there is no visible drifts in products temperature and torques required to turn the screw and by a steady extrusion rate. Temperature, both of the barrel and product were varied by continuous running of the machine, thereby building up the temperature. A major reason why heat was generated through viscous dissipation and not by addition through the barrel walls is that heat generated by drive unit (through viscous dissipation) is more dominant and cost efficient (Liang et al., 2002). Since barrel temperature varies with duration of operation, duration of operation was observed as the independent variable. Temperature was controlled by removing and dipping the barrel and screw in a bath of cold water at each run of sample. The amount of water needed to bring the samples to the required moisture content was calculated and added slowly while being stirred in a mixer.

2.4 Statistical Analysis

This experiment was conducted using a factorial design comprising of five levels of product classification, three levels of initial moisture content, three levels of screw speed and five levels of duration of operation of machine. The four independent variable levels were pre-selected based on the results of preliminary tests. Each treatment was replicated thrice. One way ANOVA, least significant follow up tests, and stepwise multiple regression analysis were carried out using Statistical Package for Social Scientists (SPSS 13.0) software while response surface regression and correlation analysis were carried out using the data analyst and response surface regression procedures of Statistical Analysis System (SAS) software v.9.R1 (2003). Also, variables were analysed with and without their interaction to see if there will be any improvement in the model fit. Microsoft Excel © 2007 was used for plotting graphs.
Regression analyses were employed to fit the experimental data to second-order polynomials.

### 2.5 Data collection and analysis

Official methods of the Association of Official Analytical Chemists (1995) were used for moisture, ash, protein, fat and crude fibre. The carbohydrate content was determined by difference. Moisture contents of native starch samples and their extrudates were determined on a dry basis by an oven method using the AOAC (1995) method 925-09. Expansion ratio of extrudates was calculated according to Choudhury and Gautam (1998). Extrudates diameters were measured using a caliper. Radial expansion ratios of the extrudates were calculated as:

\[
\frac{D^2}{d^2}
\]

where \(D\) is the extrudate’s diameter while \(d\) is the diameter of the die. Each value of extrudate diameter was an average of three readings. Also, the photographs of the expanded extrudates were taken for purposes of comparison.

### 3. Results and Discussion

The Proximate composition of all the materials under study is presented in Table 1. This result shows that the protein content of TMS 30572 variety of cassava is high when compared with other varieties used in previous studies (Badrie and Mellowes, 1991). Efforts to improve cassava have being focused on increasing yield, dry matter content, nutritional and protein content as a means to contribute to a sustainable and cost effective solution to malnutrition (Dixon et al., 2007).

![Figure 3](image3.png)

**Figure 3.** Variation of expansion ratio with initial moisture content at 30 minutes extrusion time and 100 rpm screw speed

![Figure 4](image4.png)

**Figure 4.** Variation of expansion ratio with screw speed at 30 minutes extrusion time and 30% initial moisture content

![Figure 5](image5.png)

**Figure 5.** Variation of product expansion ratio with duration of operation at screw speed 100 rpm and initial moisture content 30%

A range of feed moisture from 25-40% w.b. was selected for cassava flour, starch and wheat flour while 30 - 50% was selected for maize. This was because
F.T. Fayose: Expansion Characteristics of Selected Starchy Crops during Extrusion

samples with lower moisture contents to these ranges blocked the rotation of the screw as there was no transition from the original floury nature to a melted state typical of most extrusion processing. This may be because the moisture content was not sufficient to solvate the starch polymers and allow them to move freely in the mass. Hence there was resistance to deformation and no expansion was effected. This problem of getting stocked at lower moisture levels can be overcome by improving the torque.

The physical appearance of the extrudates arranged in order of duration of sampling (2-24) and degree of expansion are shown in Plates 1-10.
All extrudates of maize starch at higher product temperature were characterised by their appearance, porous structure and fragility. Increase in temperature of maize starch to make it possible to obtain a texture with higher porosity and greater fragility. These changes in product characteristics are a result of modification of the starch and protein components under high temperature. Also, back pressure developed in the die resulted in high initial expansion and then collapse of extrudates, after a brief time, leading to smaller diameter extrudates. Ganjyal and Hanna (2004) observed that this phenomenon was because the pressure drop exerted tensile forces in the cell material in excess of its elastic limits.

Previous studies also reported increased radial expansion with increased barrel temperature and reduced feed moisture content for corn grits and corn starch (Mercier and Feillet, 1975), rice flour (Ding et al., 2005), wheat flour (Ding et al., 2006) and cassava (Chang and EiDash, 2003). As the barrel temperature increased the viscosity of the feed material decreased resulting in better expansion (Mercier and Feillet, 1975; Lo et al., 1998; Ding et al., 2005).

Although maize starch was observed to start puffing before maize flour but it could not expand as much as maize flour because it does not develop sufficient strength/structure and adhesiveness to form a continuous matrix. Hence there were lots of bubbles in the surfaces of the extrudates making them very, very weak to touch. However, this quality makes it very suitable as ready to eat snacks product, because since it is very weak and brittle, masticating it will be very easy. All products at low extrusion time are smooth and can be suitable for pasta products.

The stepwise regression data analysis of expansion ratio is shown in Table 2. From the stepwise linear multiple regression analysis conducted, the $R^2$ was very low. But a high $R^2$ was obtained for the plot (Graph) when fitted to a sixth order polynomial trend. The interaction term Sm has the highest contribution, 6%, to $R^2$ of expansion ratio. The variable, starch content accounted for only 1.3% and protein content 13.1% of the total variation in $R^2$. This low $R^2$ for expansion ratio is an indication that it the relationship is not best described by a linear model. The (VIF) value for all parameter estimates and those of (ds, Mc, dsm) were 1.0.
Therefore, it can be concluded that multicollinearity is not a problem in this case. However, for the 3rd model of the interaction terms ds and dsm, the VIF value of 26.79 and above can be an indication that at least one of the independent variables is a perfect linear function of one or more other independent variable in the equation.

The detailed statistical analysis using response surface methodology (RSM) generated the coefficients of the second order polynomials for the response functions (eqn 1). Generally, there is an improvement in the R² (0.86) of the response surface regression model than for the stepwise regression model.

\[ Y = 2.99X_1 + 0.73X_2 + 1.65X_3 - 0.056X_4 - 0.01X_1^2 - 0.025X_2^2 - 0.0015X_3^2 + 0.0003X_1X_3 - 0.0002X_1 + 0.021X_2X_3 + 0.014X_2X_3 + 0.004X_3X_4 - 0.009X_5^2 \]

\[ \text{Eqn.2} \]

The canonical analysis indicates that the predicted response surface is shaped like a saddle. The eigenvalue of 3.32 shows that the valley orientation of the saddle is downward curved than the hill orientation, with eigenvalue of 0.99. The coefficients of the associated eigenvectors show that the value is more aligned with Duration and the hill with SS. Because the canonical analysis resulted in a saddle point, the estimated surface does not have a unique optimum. However, the ridge analysis indicates that maximum ER will result from relatively high Pc, Sc, moderate MC, high SS and moderate Duration. Note from the analysis of variance for the model that the test for the SS is not significant.

The result of one-way analysis of variance (see Table 3) shows that expansion is significantly different at 95% confidence interval at 100, 150 rpm and 200 rpm for maize flour but not for all other products. This was due to the fact that maize flour being the densest of all materials under this study requires minimum moisture content 40% to flow through the extruder.

### Table 2. Stepwise Regression of expansion ratio for all product classification

<table>
<thead>
<tr>
<th>Models</th>
<th>Coefficients</th>
<th>T-test</th>
<th>Probability</th>
<th>Adjusted R²</th>
<th>F value</th>
<th>Probability</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B_0</td>
<td>1.692</td>
<td>12.222</td>
<td>.000</td>
<td>.067</td>
<td>51.706</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>B_san</td>
<td>1.04E-005</td>
<td>7.191</td>
<td>.000</td>
<td>.000</td>
<td>51.706</td>
<td>1.000</td>
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<tr>
<td>2</td>
<td>B_0</td>
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<td>-1.270</td>
<td>.204</td>
<td>.080</td>
<td>31.332</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>B_san</td>
<td>1.04E-005</td>
<td>7.192</td>
<td>.000</td>
<td>.000</td>
<td>31.332</td>
<td>1.000</td>
</tr>
<tr>
<td></td>
<td>B_sc</td>
<td>.032</td>
<td>3.208</td>
<td>.001</td>
<td>.000</td>
<td>31.332</td>
<td>1.000</td>
</tr>
<tr>
<td>3</td>
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<td>-10.602</td>
<td>.000</td>
<td>.211</td>
<td>63.682</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>B_sm</td>
<td>1.03E-005</td>
<td>7.685</td>
<td>.000</td>
<td>.000</td>
<td>63.682</td>
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<tr>
<td></td>
<td>B_sc</td>
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<tr>
<td></td>
<td>B_pc</td>
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<td>10.869</td>
<td>.000</td>
<td>.000</td>
<td>63.682</td>
<td>1.000</td>
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</table>

### Table 3. Least significant means of products for expansion ratio

<table>
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<tr>
<th>SS</th>
<th>MC</th>
<th>GRP</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CS</td>
<td>CF</td>
</tr>
<tr>
<td>150</td>
<td>1</td>
<td>21.860</td>
<td>31.003</td>
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<tr>
<td></td>
<td>3</td>
<td>38.835*</td>
<td>18.330</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>16.975</td>
<td>-12.673</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-38.835*</td>
<td>-18.330</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-16.975</td>
<td>12.673</td>
</tr>
<tr>
<td>100</td>
<td>1</td>
<td>15.488</td>
<td>11.820</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>27.335*</td>
<td>35.503</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-15.488</td>
<td>-11.820</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>11.848</td>
<td>23.683</td>
</tr>
<tr>
<td></td>
<td>3</td>
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<td>-35.503</td>
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<td>2</td>
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<td>7.147</td>
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<tr>
<td></td>
<td>2</td>
<td>-7.145</td>
<td>20.165</td>
</tr>
</tbody>
</table>

**Remarks:** pc - protein content; sc - starch content, MC 1, 2, 3 - Moisture content 25%, 30% and 40%; Ss – screw speed; Dt - duration of operation; PT - Product temp (°C); GRP - group, CS - Cassava starch; CF- Cassava flour; MS- Maize starch; MF- Maize flour; WF- Wheat flour (-ve means negative but significant effect). Significant at *P < 0.05; ** P < 0.01.
8. Conclusion
The expansion response of the extrudates of a locally
developed single screw extruder has been well
caracterised. Expansion of maize and wheat were less
sensitive to changes in extrusion variables when
compared to cassava. Database on extrusion of the crops
under study, which are of benefit in food and feed
processing, are established. Specific end uses to which
the products at different extrusion conditions can be put
are identified. Also, the canonical analysis of the
response surface analysis resulted in a saddle point; the
estimated surface does not have a unique optimum.
However, directions on further experimentation for
optimisation are suggested.

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temperatures during extrusion which she aims to control in order
to meet their specific temperature for good quality. She is a
Registered Engineer.

■
Study of an Activated Carbon System for the Treatment of Fermentation Wastewater from a Bioethanol Production Process

George M. Mwangi and Gbekeloluwa B. Oguntimein

Abstract: The performance of activated carbon system for the treatment of wastewater from a bioethanol process was studied. Studies were performed using fermentation wastewater from bioethanol process containing salts and dissolved organics to determine the adsorption capacity of activated carbon to remove the dissolved organics. Continuous studies in a packed column containing sand and activated carbon resulted in the removal of dissolved organic compounds but the salts concentration was not significantly affected. Batch studies using the bottle point technique generated the specific adsorbate and equilibrium concentration data which fitted both the Langmuir and Freundlich isotherms with the former giving a better fit. The Freundlich capacity factor and the Freundlich intensity parameter were found to be 2.248 and 0.369, respectively. The Langmuir constant's a and b were found to be 58.82 and 0.0009, respectively. Using these parameters, a contacting system with multiple contacting beds in series is recommended due to the short bed life. Based on design calculations, for an effluent with a flow rate of 500 L/min with an empty bed contact time of 30 min allowed, 675 kg of activated carbon would be required to reduce the dissolved organic compound concentration by 74%.

Keywords: Fermentation wastewater, Activated carbon, adsorption isotherm, adsorption capacity

1. Introduction

The use of fossil fuels is associated with two major problems: depletion and global warming. Fossil fuels reserves are finite and with the current consumption rate they face depletion in the near future. According to the International Panel on Climate Change comprising of a group of scientists formed by the United Nations (UN), excessive burning of fossil fuels produces carbon dioxide and other greenhouse gases in large amounts that are causing climate change (Parry et al., 2007). Many countries (especially the developed nations) are looking into ways of producing alternative energy that is renewable, sustainable and environmentally friendly. Ethanol has over the recent past stood out as one of the potential energy sources. Corn and sugar cane have been the main raw materials for ethanol production however this scenario might affect the food prices. According to United States Department of Agriculture (USDA), dependence on corn to meet ethanol production needs affects supplies and subsequently food and feed prices (Coyle, 2007).

Research is underway to use a microbe Sacharophagus degradan isolated from the Chesapeake Bay that is capable of degrading many organic matter with subsequent fermentation of sugars to ethanol at Zymetis Inc., College Park Maryland (Hutchenson, 2008). As the process is depicted in Figure 1 the wastewater produced in the process contains water, dissolved organics (primarily proteins), salts and small amount of suspended solids (trash).

Figure 1. Bioethanol production process incorporating wastewater recycling
The total water used in bio refineries may be as high as 4 gallons of water per gallon of ethanol produced (Andy, 2007; NRC, 2008) and the effluent generated cannot be released to the environment without some form of treatment. To make the entire process more economically and environmentally friendly, the fermentation wastewater needs to be treated and recycled in the bioethanol production process. Suspended solids in the fermentation wastewater can be removed through centrifuge or using rapid sand filters. The resultant wastewater still contains dissolved organics (proteins, carbohydrates) and salts. There is therefore a need to develop a treatment process to recycle the wastewater back into the ethanol production process.

The objective of this study is to design a treatment system that will reduce the amount of dissolved organics but retain the salts which are necessary for microbial growth. This paper reports the studies on the adsorption capacity of activated carbon as a suitable medium for the treatment of fermentation wastewater from a bioethanol production process and the subsequent system for recycling the wastewater. Other methods that can be applied to remove or reduce dissolved organics in wastewater include reverse osmosis, slow sand filtration and activated sludge (Droste, 1997). Reverse osmosis would affect the salt concentration, slow sand filtration requires large land area and has low achievements in terms of dissolved organic removal (50% reduction) (Collins, 1998), and activated sludge process is associated with high operating costs and generation of solid waste that requires proper disposal. Apart from the problems associated with these methods, it would be difficult or impractical to study their performance in treating fermentation wastewater in the laboratory. These methods were therefore not suitable in this case.

2. Theory

Activated carbon as an adsorbent is often used to remove organic contaminants. It can be prepared from almost any carbonaceous material by heating it with or without addition of dehydrating chemicals in the absence of air. Activation is done to create a large surface area within the carbon which makes activated carbon ideal for adsorption. It occurs by passing mildly oxidative hot gases (carbon dioxide or steam) through the carbon at temperatures between 315°C and 925°C. This causes the formation of tiny fissures or pores (Clark and Lykins, 1989). Activated carbon can either be granular (Granular activated carbon-GAC) or powdered (Powdered activated carbon-PAC).

The amount of adsorbate that can be taken up by an adsorbent is a function of both the characteristics and concentration of adsorbate and liquid phase characteristics such as pH and temperature (Droste, 1997; Chaudhary et al., 2003). Generally, the amount adsorbed is determined as a function of the concentration at a constant temperature, and the resulting function is called an adsorption isotherm which is the basic instrument for evaluating an adsorbent’s use.

Adsorption isotherms describe the relation between the amount or concentration of adsorbate that accumulates on the adsorbent and the equilibrium concentration of dissolved adsorbate. Experiments must be conducted to gather adsorption data which is then analysed according to the following material-balance equation:

$$q_e = \frac{V(C_e - C_0)}{M}$$

where $V$ is volume of the sample (L), $C_e$ and $C_0$ the initial and equilibrium concentration of the adsorbate in solution (mg/L), $M$ is the mass of carbon in the bottle (g), and $q_e$ is adsorbent phase concentration on the carbon after equilibrium (mg adsorbate/g adsorbent). The Freundlich and Langmuir isotherms are commonly used (Wei-chi et al., 2006; Naiya et al., 2008; Hernainz et al., 2008; Shahri et al., 2010). The adsorption data is plotted to fit a linearised form of the isotherms and the correlation coefficient of the straight-line plot determines the most appropriate isotherm form. The Freundlich isotherm is defined as:

$$\frac{x}{m} = K_f C_e^{1/n}$$

where $x/m$ is the mass of adsorbate per unit mass of adsorbent (mg adsorbate/g carbon), $K_f$ is Freundlich capacity factor (mg adsorbate/g activated carbon)L water/mg adsorbate$^2$, and $1/n$ is the Freundlich intensity parameter. The constants can be determined by plotting Log $(x/m)$ versus log $C_e$ where $1/n$ is the slope of the line and $K_f$ the y-intercept.

$$\log \left( \frac{x}{m} \right) = \log K_f + \frac{1}{n} \log C_e$$

The Langmuir isotherm is defined as:

$$\frac{x}{m} = \frac{abC_e}{1 + bC_e}$$

where $a$ and $b$ are empirical constants with ‘$a$’ representing the maximum monolayer adsorption capacity (mg adsorbate/g adsorbent), ‘$b$’ has units of L/mg. The constants are also determined by plotting $C_e/(x/m)$ versus $C_e$ where $1/a$ is the slope of the line and $1/(ab)$ the y-intercept.

$$\frac{C_e}{(x/m)} = \frac{1}{ab} + \frac{1}{a} C_e$$

In a continuous fixed bed column, solution containing the adsorbate is introduced from the top of the column containing fresh adsorbent and a dynamic condition starts to develop establishing a mass transfer zone or adsorption zone. This mass transfer zone is defined as the carbon bed depth required to reduce the contaminant concentration from the initial to the final level, at a given flow rate. As shown in Figure 2, the mass transfer zone moves through a carbon bed and
reaches its exit boundary, contamination begins to show in the effluent, a condition classified as "breakthrough" and the amount of material adsorbed is considered the breakthrough capacity. $C_p$, $C_e$ and $C_b$ are the initial, exhaustion concentration and breakthrough concentration respectively. $V_b$ is the volume of water treated at breakthrough and $V_e$ volume passed through an adsorption bed at exhaustion. The time taken to reach the breakthrough point is called the time to breakthrough. If the bed continues to be exposed to the adsorbate solution, the mass transfer zone will pass completely through the bed and the effluent contaminant level will equal the influent. At that point, saturation capacity is reached. The saturated capacity is which is represented by the isotherm (Carbirol 1992).

3. Experimental Work

3.1 Continuous experiment

A continuous experiment was carried out in a packed column containing gravel, activated carbon and sand with depths of 50mm, 600mm and 80mm, respectively and filter at the bottom (see Figure 3).

A sample of fermentation wastewater from a bioethanol production process from the degradation of trash by *S. degradan* microbe provided by Zymetis Inc., University of Maryland, College Park was used. The sample of wastewater was introduced at the top and allowed to filter through the packed column with a constant head of 20mm maintained above the sand. For every 100ml of filtrate collected, the time taken to collect was recorded throughout the entire filtration process. The absorbance at 280nm and 570nm of each 100ml of filtrate collected in different containers was measured using a Gensys 5 spectrophotometer. Electrical conductivity was measured for every 300ml of the filtrate collected using the conductivity meter. The recorded times for every 100ml of filtrate collected were used to calculate the filtration rate.

3.2 Batch experiment

In the batch experiment, fixed volumes (0.2 L) of the fermentation wastewater of known concentration were added to each of ten bottles containing different amounts of activated carbon. The bottles were incubated at room temperature for 7 days after which equilibrium concentrations in each of the bottles were then determined by measuring the absorbance at 280nm. Seven days provides adequate time for the organics to adsorb onto the activated carbon to the point of saturation (Collins 1998). The measured absorbance was converted into mass concentration using the following relationship (Stoscheck 1990).

\[
\text{Concentration (mg/ml)} = \frac{\text{[Absorbance at 280 nm]}}{\text{[path length (cm)]}}
\]

\[
\text{Concentration (mg/L)} = \frac{\text{[Absorbance at 280 nm]}}{\text{[path length (cm)]}} \times 10^3
\]

This is a rough estimation of the concentration of unknown proteins or protein mixtures (dissolved organics). The path length is the light path through the cuvette which is equal to 1cm. The adsorption data was analysed using the mass-balance equation to obtain data that was used in the Langmuir and Freundlich isotherms.

4. Results and Discussions

Figure 4 shows the conductivity of the column effluent which was fairly constant over filtrate volume of 3600ml. Figure 5 shows the filtration rate profile. The filtration rate decreased from about 0.88mm$^3$/mm$^2$/sec to 0.58mm$^3$/mm$^2$/sec over 7000ml of filtration. The concentration of dissolved organic compounds was indirectly measured by measuring the absorbance at 280nm. Proteins in solution absorb ultraviolet light with absorbance maxima at 280 and 200 nm. Amino acids with aromatic rings are the primary reason for the absorbance peak at 280 nm (Stoscheck, 1990).
Figure 6 shows the absorbance at 280nm for the column effluent. The initial absorbance of the wastewater was 3.90 and that of the initial column effluent was 3.63. Over the next 2,600ml volume of effluent, the absorbance was fairly constant before increasing to 3.90. Similarly, the clarity of the column effluent was monitored by measuring the absorbance at 570nm. Figure 7 shows the absorbance at 570nm of the column filtrate. The absorbance of the initial wastewater was 0.295 while that of the initial column effluent was 0.250 and was fairly constant at this value for the first 2700ml of column effluent.

The mass concentrations were determined using the relationship for rough estimation of the concentration of unknown proteins or protein mixtures:

\[
\text{Concentration (mg/L)} = \frac{\text{Absorbance at 280 nm}}{\text{path length (cm)}} \times 10^3
\]

The results for the specific adsorbate \( q \) and the equilibrium concentration \( C_e \) were plotted to obtain the adsorption isotherm in Figure 8, and fitted to the linearised Freundlich and Langmuir isotherms in Figures 9 and 10, respectively. The Freundlich capacity factor \( K_f \) is given by the intercept when \( C_e = 1 \) and is equal to 2.248. The Freundlich intensity parameter \( 1/n \) is given by the slope of the line = 0.369. Thus, the Freundlich isotherm in this particular case is defined by:

\[
q = \frac{x}{m} = 2.248C_e^{0.369}
\]

The value of empirical constants \( 1/ab \) is given by the intercept when \( C_e = 0 \) and is equal to 18.985. The value of \( 1/a \) is given by the slope of the line = 0.017

\[
1/(ab) = 18.985; \ 1/a = 0.017; \ a = 58.82 \text{ mg/g}
\]

The packed column studies established that activated carbon was a suitable medium to remove dissolved organics and did not affect the amount of salts in the wastewater significantly as indicated by the absorbance values at 280 nm and electrical conductivity values, respectively. The electrical conductivity was an indicative measure of salts in the wastewater. The decrease in the filtration rate is an indication of clogging due to suspended solids getting trapped within the sand. Backwashing would therefore be necessary to remove the accumulated solids.
The breakthrough volume, which is indicative of the useful period of activated carbon after which it should be replaced or regenerated, for this study was 2600ml. Figure 7 represents the clarity measure of the filtrate and after 2,700ml of filtration through the packed column, the filtrate becomes cloudy, an indication that the media needs to be regenerated.

In Figure 8, the vertical axis \( q_e \) represents the dissolved organic uptake per mass of activated carbon, the plateau observed means that there is a decrease of the active sites for adsorption indicating the maximum uptake capacity of the activated carbon for dissolved organics. The experimental data plotted on a log-log graph determines the Freundlich capacity factor and intensity parameter \( K_f \) and \( 1/n \), respectively. In Figure 8, the linearised plot determines constants \( a \) and \( b \) for the Langmuir isotherm. Adsorption characteristics of activated carbon used in wastewater treatment are normally best described by the Freundlich isotherm (Tchobanoglous et al., 2002). Experimental data for activated carbon usually fits the Langmuir isotherm poorly. However, considering the correlation coefficient \( R^2 \) values in Figures 8 and 9 (0.9547 and 0.9869, respectively), the Langmuir isotherm was a better fit in this study. This could be attributed to the high organic concentration present in the wastewater. Langmuir isotherm accounts for surface-coverage in that when the fluid concentration is very high, a monolayer forms on the adsorbent surface.

5. Analysis
An analysis for an activated carbon contactor designed to treat wastewater similar to the sample used in the experiment is carried out below. As of 2006, different ethanol biorefineries in the US had capacities ranging 1-1,000 million gallons per year (mgy) (RFA, 2006). 97% of the plants had capacities ranging 1-100 mgy most of which were below 50 mgy. Considering a water consumption of up to 3 gallons water per 1 gallon ethanol produced, wastewater production is expected to be about 2 gallons per 1 gallon of ethanol. Therefore, a typical plant with an average production capacity of 35 mgy ethanol is expected to produce 70 mgy wastewater. This is about 504 L/min. For the purposes of analysis, 500 L/min will be used and a single bed will be considered. With the following information:

- \( C_0 = 3820 \text{ mg/L (experimental)} \)
- \( C_e = 1000 \text{ mg/L, GAC density} \)
- \( \rho_{\text{GAC}} = 450 \text{ g/L, } a = 58.82 \text{ mg/g;} \)
- \( b = 0.0009 \text{ L/mg (experimental)} \)

Carbon usage rate:

\[
\frac{m_{\text{GAC}}}{V} = \frac{C_0 - C_e}{q_e} - \frac{C_e - C_{\text{eq}}}{\frac{abC_e}{1+bc}} = \frac{(C_e - C_{\text{eq}})}{\frac{abC_e}{1+bc}}
\]

\[
= \frac{(3820 - 1000)}{\text{mg/L}} \left( 1 + 0.0009 \times 1000 \text{mg/L} \right)
\]

\[
= 101.2 \text{ g GAC/L}
\]
From typical design values for granular activated contactors (Sontheimer 1988; Nazaroff and Cohen 2001), if a bed volume of 15 m$^3$ is chosen (from the provided range 10-50 m$^3$), the empty bed contact time (EBCT) is given as:

$$EBCT = \frac{Volume}{Flowrate} = \frac{15000L}{500L/min} = 30\text{min}$$

The mass of carbon required for a 30 min EBCT:

$$m_{GAC} = V_b \rho_{GAC} = EBCT * Q * \rho_{GAC}$$

where $V_b$ is the volume of GAC in contactor

$$= 30\text{min} * (500 \text{L/min}) * (450\text{g/L})$$

$$= 6.75 \times 10^6 \text{g}$$

The volume of wastewater treated using a 30 min EBCT:

$$= \frac{\text{mass of GAC for given EBCT}}{\text{GAC usage rate}} = \frac{6.75 \times 10^6 \text{g}}{101.2g\text{GAC}/L} = 66700L$$

Bed life

To treat an effluent with a flow rate of 500 L/min (approximately 190,000 gal/d) and concentration of 3820 mg/L down to a concentration of 1000mg/l and with an empty bed contact time of 30 min allowed, 6.75 x $10^6$ g of granular activated carbon is required. The total volume of effluent that will be treated will be 66,700 L (17,620 gal). However, the bed life which is approximately 2 hours is too short.

A schematic depicting the configuration of the process designed to remove dissolved organics from fermentation wastewater from a bioethanol plant is shown in Figure 11. At least two systems of sand filter units and activated carbon beds are set up in parallel to ensure continued operation while servicing the beds. Activated carbon beds are further set up in series to take full advantage of the adsorption capacity difference between breakthrough and saturation.

**Figure 11. Organic removal process**

### 6. Conclusions

The adsorption isotherms determined based on experimental data, show that activated carbon has the capacity to reduce dissolved organics in effluent from a bioethanol production process. The isotherms can be used to optimise activated carbon columns. Based on design calculations, for an effluent with a flow rate of 500 L/min with an empty bed contact time of 30 min allowed, 675kg of activated carbon would be required to reduce the dissolved organic compound concentration by 74%. To increase the bed life, greater carbon depth or beds in series are desired. This consequently increases the time after which the beds should be serviced. Multiple beds in series as mentioned earlier take full advantage of the adsorption capacity difference between breakthrough and saturation and thus can be used to increase this time. Increasing the volume of the beds will also increase the bed life. These findings and conclusion sets up a platform for further work to find systems and configurations that optimise the treatment efficiency.

Due to the large amounts of activated carbon that may be required to treat the fermentation wastewater (depending on the desired effluent concentration) it is necessary to incorporate carbon regeneration in order to save on the cost that would be incurred in replacing and disposing spent (saturated) carbon.

### Acknowledgement

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### References:


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Identification and Remediation of Water-Quality Hotspots in Havana, Cuba: Accounting for Limited Data and High Uncertainty

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Abstract: A team at the University of Miami (UM) developed a water-quality model to link in-stream concentrations with land uses in the Almendares River watershed, Cuba. Since necessary data in Cuba is rare or nonexistent, water-quality standards, pollutant data, and stormwater management data from the state of Florida were used, an approach justified by the highly correlated meteorological patterns between South Florida and Havana. A GIS platform was used to delineate the watershed and sub-watersheds and breakdown the watershed into urban and non-urban land uses. The UM model provides a relative assessment of which river junctions were most likely to exceed water-quality standards, and can model water-quality improvements upon application of appropriate remediation strategies. The pollutants considered were TN, TP, BOD5, fecal coliform, Pb, Cu, Zn, and Cd. The key model result is that the river junctions most likely to exceed water-quality standards are at the intersections of upstream sub-watersheds, and the best way to reduce the concentrations is via better management of the runoff from the upstream sub-watersheds. Dilution and attenuation were significant factors in reducing the concentration at downstream river junctions. The model was conservative in that it did not consider point-sources or groundwater dynamics in the Almendares River, and was found to be comparable to an established USGS water-quality model. The UM model is a valuable tool in assessing the water quality in the Almendares River and can be applied similarly to other rivers in Cuba or in similar countries with water-quality problems and limited data availability.

Keywords: Almendares River, water-quality model, infrastructure, Cuba

1. Introduction

An accurate assessment of the water quality in a stream is of great benefit to society as it reflects the condition of the surrounding natural and man-made environment and can provide warning in case of risk to human health. Normal riverine activities such as bathing and boating, or using the river as a source for drinking water can expose communities to significant risk of illness or fatality if the waters have high toxic or pathogenic content. Likewise, the consumption of fish exposed to toxic substances in the water can greatly increase risk to human health. The conventional approach to managing the quality of water in streams is to control the input of contaminants into the stream from point sources and non-point sources such that applicable water-quality standards are met. However, water-quality problems tend to be greater in lesser-developed countries like Cuba where regulatory standards, relevant scientific data, and enforcement of standards are rare or nonexistent.

To address the problems of limited data and minimal regulations which are particularly prevalent in Cuba, a water-quality model was developed to simulate the effects of stormwater runoff on the stream water quality in the Almendares River watershed, which is home to roughly 2.5 million people and includes the capital city of Havana. Upper and lower portions of the watershed were considered separately, where the runoff was routed from the upper region to the Ejército Rebelde reservoir and from the lower region below the reservoir to the Almendares River’s outfall to the sea. The model links land use and runoff to predict in-stream concentrations and assesses uncertainty in light of the significant data limitations. The model identifies the locations in the Almendares River where the greatest water-quality problems are most likely to occur and can predict the water-quality improvements that would result from the implementation of various levels of stormwater control.

The development and application of the model as described in this report can serve as a protocol for
addressing water quality in other parts of Cuba or in similar countries with limited resources and data. The model was developed by a team at the University of Miami (UM) specifically for application to conditions in Cuba and is referred to in this report as the UM model.

2. UM Model

The UM model is formulated for watersheds that contain a network of streams, with each stream segment receiving direct runoff from a sub-area (sub-watershed) within a single overall watershed. Pollutant concentrations are predicted at sub-watershed pour-points from pollutant loads in sub-watershed runoff, where each sub-watershed is divided into “urban” and “non-urban” land uses. The runoff, \( Q_{sw} \) (m³/yr), from each sub-watershed is determined using the relation

\[
Q_{sw} = Q_1 + Q_2 = R(C_1A_1 + C_2A_2)
\]

where \( R \) is the annual rainfall (m), \( C \) (dimensionless) and \( A \) (m²) are the runoff coefficient and land area, respectively, and the subscripts 1 and 2 correspond to the urban and non-urban land uses, respectively. The pollutant load in the runoff, \( L \) (kg/yr), for each sub-watershed is determined using the relation

\[
L = Q_1e_1 + Q_2e_2 = R(C_1A_1e_1 + C_2A_2e_2)
\]

where \( e \) (typically in mg/L) is the event-mean concentration (EMC) per land use. The average-annual concentration at the pour-point of each sub-watershed, \( c_{sw} \), as shown in Figure 1a is then given by

\[
c_{sw} = \frac{L}{Q_{sw}}
\]

When stream segments exiting two neighboring sub-watersheds combine at a junction as illustrated in Figure 1b, the streamflows are summed and the average concentration at the junction, \( c \), is determined using a flow-weighted average

\[
c = \frac{Q_1c_1 + Q_2c_2 + \sum Q_{ui}c_{ui}}{Q_1 + Q_2 + \sum Q_{ui}}
\]

where \( Q_i \) and \( c_i \) are the flow and concentration in segment \( i \) derived from the sub-watersheds contributing directly to segment \( i \), \( Q_{ui} \) is the flow entering segment \( i \) from an upstream segment, and \( c_{ui} \) is the corresponding attenuated concentration from the upstream segment. Figures 1a and 1b show the mass balances for a typical watershed and a junction, respectively.

Attenuation represents the processes by which pollutant concentrations are reduced over the course of a stream segment. The primary attenuation mechanism is sedimentation, where pollutants sorbed to suspended sediment particles are removed as suspended particles settle to the bottom of the stream, thereby reducing the in-stream concentration of the pollutants. The UM model accounted for the attenuation of concentrations from an upstream segment over the length of a downstream segment using the first-order relationship

\[
c_a = c_e \exp(-Kx)
\]

where \( c_a \) is the attenuated concentration at the end of the lower stream segment [ML⁻³], \( c_e \) is the concentration at the end of the upper stream segment [ML⁻³], \( K \) is the attenuation factor [L⁻¹], and \( x \) [L] is the length of the downstream segment. The attenuation factor was assumed to be 1000 m⁻¹ based on flow rates for certain stream reaches in Havana as stated in Egues and Diaz (1997) and approximate stream dimensions. A sensitivity study and discussion of this assumed value for \( K \) are included in a later section.

2.1 Uncertainty Analysis

An uncertainty analysis was conducted to quantify the uncertainty in model predictions and provide 90%-confidence intervals around average concentrations predicted by the UM model. Due to the natural topography of the Almendares River watershed, the mean and variance of both the flow and concentration contributed by each sub-watershed were found first, then these contributions were combined cumulatively at the downstream junctions where stream segments intersect. Mean flow from each sub-watershed was found using Equation 1 with the averaged value of each variable. The corresponding variance in flow, \( \sigma^2_{Q_{sw}} \), at the exit of a sub-watershed was determined by the first-order relation
\[ \sigma^2_{j} = (RA_i)^2 \sigma^2_{c_i} + (RA_i)^2 \sigma^2_{c_u} \]  
(6)

where the subscripts 1 and 2 correspond to urban and non-urban land use, respectively, and \( \sigma^2_{c_i} \) and \( \sigma^2_{c_u} \) are the variances in the runoff coefficients considered in the model per land use. At each junction, the mean flow leaving the junction is equal to the sum of the average flows entering the junction. The variance in flow leaving the junction, \( \sigma^2_{j} \), is the sum of the variances of flows entering the junction

\[ \sigma^2_{j} = \sigma^2_{c_i} + \sigma^2_{c_u} + \sum_{i=1}^{2} \sigma^2_{\phi_{i}} \]  
(7)

where \( \sigma^2_{c_i} \) is the variance in the direct runoff to the \( i^{th} \) stream segment, and \( \sigma^2_{c_u} \) is the variance in the flow contributed by the \( i^{th} \) upstream segment.

The mean concentration in the runoff from a subwatershed, \( c_{sw} \), was calculated using Equation 3 with mean values of the variables, while at the junctions the mean concentration of the flow leaving the junction is equal to the flow-weighted value given by Equation 4. To determine the variance in the concentration in streams exiting from subwatersheds and junctions, \( \sigma^2_{c} \), a first-order second-moment analysis was conducted by using (Benjamin and Cornell, 1970)

\[ \sigma^2_{c} = \left( \frac{\partial c}{\partial c_i} \right)^2 \sigma^2_{c_i} + \left( \frac{\partial c}{\partial c_j} \right)^2 \sigma^2_{c_j} + \left( \frac{\partial c}{\partial \phi_{i}} \right)^2 \sigma^2_{\phi_{i}} + \left( \frac{\partial c}{\partial \phi_{j}} \right)^2 \sigma^2_{\phi_{j}} \]  
(8)

where the partial derivatives of \( c \) derived from Equation 4 are:

\[ \frac{\partial c}{\partial c_i} = \frac{Q_i}{Q_j} \]  
(9)

\[ \frac{\partial c}{\partial c_j} = \frac{Q_j}{Q_j} \]  
(10)

\[ \frac{\partial c}{\partial \phi_{i}} = \frac{Q_i - Q_c}{Q_j} \]  
(11)

\[ \frac{\partial c}{\partial \phi_{j}} = \frac{Q_j}{Q_j} \]  
(12)

The partial derivatives were evaluated using the expected (average) values of all quantities in the calculation. At the subwatershed exits, the variances \( \sigma^2_{c_i} \) and \( \sigma^2_{c_j} \) were derived from the pollutant EMCs per land use and \( \sigma^2_{\phi_{i}} \) and \( \sigma^2_{\phi_{j}} \) were determined using Equation 6. At the junctions, \( \sigma^2_{c_i} \) and \( \sigma^2_{c_j} \) were either derived from input pollutant data (discussed in a later section) or taken from upper stream segments depending on the watersheds intersecting at each junction. Similarly, \( \sigma^2_{\phi_{i}} \) and \( \sigma^2_{\phi_{j}} \) were determined from Equation 6. In cases where an upstream segment is present, the variance in concentration (not flow) was attenuated according to Equation 5, where \( c_i \) and \( c_u \) were replaced with the appropriate \( \sigma^2_{c_i} \).

### 3. USGS Model

The UM model was compared with the USGS water-quality model as a reference point. The USGS model is described by (Chin 2006a):

\[ Y = 0.454(N)(BCF)(a + b \sqrt{C}) + (ID) + (MAR) + (MJT) + (X2) \]  
(13)

where \( Y \) is the yearly pollutant load (kg), \( N \) is the average number of storms per year, \( BCF \) is a bias correction factor, \( DA \) is the total contributing drainage area (ha), \( IA \) is the impervious area as a percentage of the total contributing area (%), \( MAR \) is the mean annual rainfall (cm), \( MJT \) is the mean minimum January temperature (°C), \( X2 \) is an indicator variable related to land use, and the remaining parameters are shown in Table 1. The values used for this analysis were \( N = 70, IA = 30\% , MJT = 16°C, \) and \( X2 = 1 \) if the urban area is greater than 75% of the contributing area and 0 otherwise. Parameters for the USGS model are available for the five pollutants shown in Table 1.

### 4. Model Parameters

#### 4.1 Rainfall-Runoff Parameters

There is little available rainfall data in Cuba for runoff modeling. However, due to the close proximity of Havana to South Florida as shown in Figure 2, the validity of using rainfall data from South Florida as a surrogate for rainfall in Havana was investigated. A comparison of the monthly rainfall characteristics in Miami and Havana is shown in Figure 3 (www.climatetemp.info). These data show that Miami and Havana follow the same seasonal trends with peak rainfall amounts in June and September/October, wet seasons from March-September, and dry seasons from October-February. Additional climate data gathered included average annual temperature, average number of wet days per year (> 0.1 mm), average relative humidity, and average wind speed; these data are shown in Table 2 (www.climatetemp.info).

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>BCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>TN</td>
<td>-0.2433</td>
<td>0.1018</td>
<td>0.0061</td>
<td>-</td>
<td>-</td>
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<td>1.345</td>
</tr>
<tr>
<td>TP</td>
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<td>0.1294</td>
<td>-</td>
<td>0.00921</td>
<td>-0.0383</td>
<td>-</td>
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<tr>
<td>Cu</td>
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<td>0.1136</td>
<td>-</td>
<td>-</td>
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<td>-</td>
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<tr>
<td>Pb</td>
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<td>0.0070</td>
<td>0.00504</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>Zn</td>
<td>-1.6302</td>
<td>0.1267</td>
<td>0.0072</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.322</td>
</tr>
</tbody>
</table>

Source: Taken from Chin (2006a)
The analysis presented here was based on the average rainfall characteristics at several rainfall stations in South Florida, and the average annual rainfall at these stations is compared with that of Havana in Figure 4.

Note that the monthly data plotted for Miami and Havana in Figure 3 was taken from the same source (www.climatetemp.info) for purposes of comparison, while the data shown for the US stations in Figure 4 came from the National Climatic Data Center (NCDC) and the value for Havana came from a Cuban source (Hernández and Mon, 1996). The use of different sources to establish monthly rainfall patterns and yearly totals was necessary since the NCDC did not provide data for Havana. The use of different sources explains the differences in total rainfall, where Figure 3 shows Miami receiving more rainfall than Havana while Figure 4 shows Havana receiving more rainfall than Miami. The annual rainfall at the South Florida stations ranged from 1344 mm/year at St. Lucie New Lock 1 to 1485 mm/year at West Palm Beach International Airport as shown in Figure 4, which also shows that Havana averages 1411 mm/year, falling within the range of the five South Florida stations.

Using spatially-averaged hourly rainfall measurements in South Florida, Harper and Baker (2007) developed a table of runoff coefficients depending on the runoff properties of the land surface. The runoff coefficient, $C$, represents the ratio of annual runoff depth to the annual precipitation depth, described by

$$C = \frac{\text{annual runoff (mm)}}{\text{annual rainfall (mm)}}$$  \hspace{1cm} (14)

and is in the range [0-1.0]. The $C$ values reflect the average runoff/rainfall ratio for a given meteorological monitoring site over the entire available period of record, which was typically 30 years or more for the stations used by Harper and Baker (2007) to describe South Florida rainfall (see Figure 4). The runoff coefficients were determined as a function of curve number (CN) and directly-connected impervious area (DCIA), where CN is a widely used parameter for predicting direct runoff for various soil conditions and land uses, and DCIA refers to those areas that are in direct hydraulic connection to the conveyance system (i.e. storm drains) without flow over pervious areas or infiltration into the ground. The UM model was set up such that urban and non-urban land uses were characterized by CN ranges of 85-98 and 60-75, respectively, and by DCIA ranges of 65-85% and 0-15%, respectively, and the corresponding $C$ values are shown in Tables 3a and 3b. The ranges of CN and DCIA selected were assumed to be representative of land types and land uses in the Almendares watershed and were used to determine the mean and standard deviation of the runoff coefficient used in the concentration predictions and uncertainty analysis of water quality in the watershed. The average yearly rainfall for Havana, $R$, shows...
was assumed to be 1411 mm.

**Table 3a. Runoff coefficient versus Curve Number and DCIA in urban areas**

<table>
<thead>
<tr>
<th>DCIA</th>
<th>65</th>
<th>70</th>
<th>75</th>
<th>80</th>
<th>85</th>
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</thead>
<tbody>
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<td>0.679</td>
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<td>0.750</td>
<td>0.760</td>
<td>0.769</td>
<td>0.779</td>
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</tbody>
</table>

**Table 3b. Runoff coefficient versus Curve Number and DCIA in non-urban areas**

<table>
<thead>
<tr>
<th>DCIA</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
</tr>
</thead>
<tbody>
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<td>0.095</td>
<td>0.132</td>
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</tr>
<tr>
<td>65</td>
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<td>0.110</td>
<td>0.147</td>
<td>0.183</td>
</tr>
<tr>
<td>70</td>
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<td>0.129</td>
<td>0.165</td>
<td>0.201</td>
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<tr>
<td>75</td>
<td>0.120</td>
<td>0.155</td>
<td>0.189</td>
<td>0.223</td>
</tr>
</tbody>
</table>

### 4.2 Land Uses

An up-to-date digital map with shape file data for Havana was not available, so the most recent digital map was used. The map was derived from the WGS1984 data set with the latest revision circa 2004. This is the most recent revision of the World Geodetic Systems reference frame for the Earth and is the standard for both cartography and navigation.

The Havana area is referenced in the WGS1984 Zone 17 North data set, which is bound by the Northern hemisphere and stretches from 84°W to 78°W on the world map. A standard spatial reference frame is then created for the Earth’s surface and allows for area measurements to be calculated within ArcGIS. A resolution of 1:6000 was chosen for the analysis as a balance between the amount of area to be analyzed and the ability to determine the landscape and land use in the watershed. The watershed boundary was estimated via interpolation from a digital elevation map. Using ArcGIS 10, all visible river and stream segments within the watershed at a resolution of 1:6000 were mapped as polylines.

The sub-watershed boundaries are identified in Figure 5. Sub-watersheds for all streams were subsequently delineated within the final watershed boundary based on identifiable stream segments in the Almendares River and its tributaries both upstream and downstream of the Ejército Rebelde Reservoir. A map from the Cuban Heritage Collection at the University of Miami was also used as a reference for stream location and watershed boundaries (University of Miami, Cuban Map Collection).

Land areas were mapped as polygons within each digitally-created sub-watershed, and land uses within each sub-watershed were visually classified as either urban or non-urban areas. Urban areas, shown in white, represent developed lands used for both residential and commercial purposes, while non-urban areas shown in green represent farmlands, forests, undeveloped land, or areas where expanses of row crops could clearly be seen from the satellite image (see Figure 5). The field calculator within ArcGIS 10 was used to calculate area values of each individual urban or non-urban polygon as well as each stream polyline. These values were then summed corresponding to each respective sub-watershed for use in the water-quality model.

### 4.3 Event-Mean Concentrations (EMCs)

The event-mean concentration is defined as the average mass of pollutant per unit volume of runoff. Pollutants often characterized by EMCs are heavy metals, five-day BOD, total suspended solids, total nitrogen, total phosphorus, soluble species of nitrogen and phosphorus, and indicators of pathogenic bacteria such as fecal coliforms and *E. coli*. The eight pollutants commonly found in stormwater runoff that were selected for inclusion in this study were: five-day BOD (BOD5), total nitrogen (TN), total phosphorus (TP), Lead (Pb), Copper (Cu), Zinc (Zn), Cadmium (Cd), and fecal coliform (FC). One previous study examined some of these constituents in riverbed sediment of the Almendares River (Olivares-Rieumont et al., 2005), however the focus of the present study is contaminants contained in the stream flow rather than in the sediment.

Published EMC data for Cuba were unavailable. However, since land use is the primary factor in
determining EMCS, available EMC data from the United States was used (Chin, 2006b; Gain, 1996; Keith and Schnars, 2007; Migliaccio and Castro, 2009; FDEP, 2010). The published EMCS were organized by land use, varying from “mixed” or “urban” to “religious facilities” and “transportation”. For the purpose of the current study, land uses were considered as either urban or non-urban, and the values for each pollutant were combined to determine a mean, standard deviation, and coefficient of variation of the EMC.

An example of the EMC data for lead (Pb) is illustrated in Figure 6 for both urban and non-urban land uses. The Gaussian distribution shown was calculated from the mean and standard deviation for Pb in each land use taken from the National Urban Runoff Project (NURP) (Chin, 2006b). The distributions shown contain four standard deviations greater than and less than the mean. For each concentration value, the probability density was calculated using the normal distribution. Figure 6a and 6b depict the urban and non-urban EMC distributions, respectively.

The individual points on the abscissa of each graph are all values from the individual EMC sources used in this study. The relative size of these points on the axis denotes the number of sources that had the same EMC value for the constituent. Comparing the individual EMC results with the statistical results of the NURP data, it is apparent that there are some outliers on both the upper and lower ends. However many of the data points are inside the curve, and the mean of the data is within the range of the probability distribution of the NURP data. This same analysis was performed for the eight pollutants considered in this study, and the majority of data points from individual studies were found to be within the Gaussian distribution fitted to the NURP data.

The available EMC data for each contaminant/land-use scenario were combined to determine an overall mean and standard deviation of the EMC for the given scenario. The results of these calculations are shown in

Table 4. Event-mean concentrations and water-quality standards

<table>
<thead>
<tr>
<th></th>
<th>Urban Land</th>
<th>Non-Urban Land</th>
<th>Florida Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std Deviation</td>
<td>Mean</td>
</tr>
<tr>
<td><strong>BOD₅ (mg/L)</strong></td>
<td>10.90</td>
<td>5.77</td>
<td>3.03</td>
</tr>
<tr>
<td><strong>TN (mg/L)</strong></td>
<td>1.64</td>
<td>0.45</td>
<td>1.77</td>
</tr>
<tr>
<td><strong>TP (mg/L)</strong></td>
<td>0.30</td>
<td>0.26</td>
<td>0.36</td>
</tr>
<tr>
<td><strong>Pb (μg/L)</strong></td>
<td>97.7</td>
<td>104.0</td>
<td>55.4</td>
</tr>
<tr>
<td><strong>Cu (μg/L)</strong></td>
<td>33.0</td>
<td>33.9</td>
<td>44.5</td>
</tr>
<tr>
<td><strong>Zn (μg/L)</strong></td>
<td>349.8</td>
<td>1239.6</td>
<td>168.5</td>
</tr>
<tr>
<td><strong>Cd (μg/L)</strong></td>
<td>6.7</td>
<td>8.4</td>
<td>1.7</td>
</tr>
<tr>
<td><strong>Fecal coliform (CFU/dL)</strong></td>
<td>3000</td>
<td>1100</td>
<td>2300</td>
</tr>
</tbody>
</table>

4.4 Water-Quality Standards

The State of Florida water-quality standards were used as a basis for assessing water quality in the streams of Havana (FDEP, 2010). Water-quality standards are available for five different designated water uses (Class I to Class V), and Class III standards were applied in this study. The designated uses of Class III waters are: fish consumption, recreation, propagation and maintenance.
of a healthy, well-balanced population of fish and wildlife. Class III has two subcategories: primarily fresh waters and primarily marine waters; the fresh water standards were used in this study.

There are currently no numeric water-quality standards for BOD₅, TN, or TP in Florida. For the four heavy metals (Pb, Cu, Zn, Cd), the standards are determined by an equation that is a function of the hardness of the water. The equation uses a hardness value of 25 mg/L for any hardness less than 25 mg/L, a hardness value of 400 mg/L for any hardness greater than 400 mg/L, and the actual hardness in the range 25-400 mg/L. Based on a study by the U.S. Geological Survey (Briggs and Ficke, 1977), a significant portion of Florida is in the same range of hardness (121-180 mg/L CaCO₃). In addition, the USGS study also analyzed the island of Puerto Rico, which was also found to be in the 121-180 mg/L range for hardness. For the purposes of this study, the water quality standards applied for the metals were the average of the values found using a hardness of 25 mg/L and 400 mg/L. This assumed similarity between Havana and South Florida is further justified since Havana, like South Florida, is underlain by a karst aquifer (Suckow, 2003).

5. Results and Discussion

Water-quality simulations were performed for all eight pollutants of concern. Most of the results showed similar patterns, and these results will be shown here in detail for lead (Pb) and summarized for the remainder of the pollutants. The water-quality predictions for concentrations of Pb with 90% confidence intervals (CI) in the stream junctions of the main stem of the Almendares River for upper and lower regions are shown in Figure 7a and 7b, respectively.

The junctions shown are for both the upper region (above the Ejército Rebelde reservoir) in Figure 7a, and for the lower region (below the Ejército Rebelde reservoir) in Figure 7b. The junctions plotted in Figure 7b are, from left to right, 119, 118, 117, 116, 115, 114, 113, 111, 110, 106, 103, 101, 100 (coast) and can be seen in Figure 8.

It was found that the relative distribution of concentrations at the stream junctions were similar for different pollutants, and primarily varied in scale depending on the mean and standard deviation of the EMC of each pollutant. In other words, the shape of the distribution of concentrations shown in Figure 7 was consistent for all pollutants, but the magnitude of the concentrations depended on the value of the EMCs. The distribution of the concentrations does not change because the modeled flows are a function of the runoff coefficients and the landscape, which do not change between pollutants. As a reference point in Figure 7 the Florida Class III water quality standard for Pb is also shown (9.6 µg/L), and it can be seen that five of the stream junctions in the lower region and all three junctions in the upper region violate this water-quality standard.

In the lower region of the Almendares River watershed, the locations of the three highest junction concentrations (119, 118, 117) all occur farthest upstream while the average concentration decreases downstream approaching the coastline. Although the coastal areas are highly urbanized and therefore more susceptible to contamination by surface runoff, the lower concentrations that are found in the lower reaches of the Almendares River are likely due to dilution from greater flows and from attenuation over the river distance travelled.

Moreover, the predicted concentrations at the three most-upstream junctions are close to the pollutant EMC values listed in Table 4. This pattern was repeated at four other junction locations (102, 105, 109, and 112) which are not located on the main river stem but are shown in relation to the main stem in Figure 8. Each of these
junctions represents the union of two individual sub-watersheds without contribution from upstream segments, and the predicted concentrations at these junctions are near the EMC values. This result further demonstrates that junctions of upper sub-watersheds are most likely to violate water-quality standards, regardless of proximity to the coast or urban/non-urban land-use distribution, and that dilution and attenuation serve to reduce concentrations downstream after the summing of flow from several junctions.

The only way to reduce concentrations to meet water-quality standards is to reduce the EMC via better management of sub-watershed runoff. An example of such action in both upper and lower regions can be seen in Figures 9a and 9b, where the urban and non-urban EMC for Pb were reduced to 9.6 μg/L from 97.7 μg/L and 55.4 μg/L, respectively. The reduction in EMC was shown to produce mean junction concentrations that do not violate the water quality standard.

The assumption that contaminant attenuation in streams could be characterized by $K = 1,000 \text{ m}^{-1}$ as assumed in Figure 7 was examined to better understand the sensitivity of the results to the assumed attenuation factor. This sensitivity was investigated by using the UM model with $K = 100 \text{ m}^{-1}$ and $K = 10000 \text{ m}^{-1}$, which yielded the results shown in Figure 10a and 10b, respectively. It can be seen that $K$ values of 100 m$^{-1}$ and 1000 m$^{-1}$ produced little change in the shape and scale of the distribution of the average concentrations. Using a value of $K = 10,000 \text{ m}^{-1}$, however, created more noticeable changes in the shape and scale of the distribution. The most important observation is that the junctions with the most severe water-quality violations do not change as $K$ varies, thereby justifying the use of $K = 1,000 \text{ m}^{-1}$.
Figure 10b. Pb concentrations for attenuation factor, \( K = 10,000 \text{ m}^{-1} \)

The contaminant loads in both upper and lower regions predicted by the UM model are compared to the contaminant loads predicted by the USGS model in Figures 11a and 11b, respectively.

Based on these results, it is apparent that the difference between the USGS and UM model depends on sub-watershed land area; the range of areas in the upper and lower region are 80-2972 ha and 2-7571 ha, respectively. The UM model yielded contaminant loads comparable to the USGS model for sub-watersheds with areas roughly in the middle of the range of areas, such as sub-watersheds 41 (224 ha), 42 (257 ha), and 44 (221 ha) in the upper region and sub-watersheds 6 (107 ha), 26 (250 ha), and 31 (134 ha) in the lower region. However, in the two largest sub-watersheds in the upper and lower regions, 53 (2972 ha), 51 (2237 ha), 36 (7571 ha) and 34 (1348 ha), respectively, the USGS models predicted loads that were several orders of magnitude larger than the UM model.

Similarly, the two smallest sub-watersheds in the upper and lower regions, 47 (80 ha), 52 (184 ha), 28 (2 ha), and 3 (4 ha), respectively, had the smallest magnitude of USGS loads. This is likely due to the fact that the USGS model (Equation 13) has the land-area term \( DA \) in the exponent of the equation, therefore increasing its sensitivity in the overall model output. The USGS model predicted greater loads than the UM model in most sub-watersheds in the upper region while the greater load was roughly split between the models in the sub-watersheds of the lower region.

All of the results presented in detail were for Pb, because it was applicable in the USGS model and because Class III water-quality standards were available. Table 5 shows a summary of the other pollutants considered with available water-quality standards, where the number of junctions with predicted concentrations that exceeded the water-quality standard is provided.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>FC</th>
<th>Pb</th>
<th>Cu</th>
<th>Zn</th>
<th>Cd</th>
<th>FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Region (# of exceedances)</td>
<td>7</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Upper Region (# of exceedances)</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

The main stems in the lower and upper regions incorporated 13 and 3 junctions, respectively. The top-three locations with most serious water-quality violations for Pb were also the top-three locations where violations of water-quality standards by the other constituents are expected to occur.

Finally, the methodology presented in this paper for developing a model is unorthodox and needs to be evaluated objectively. The main hindrance in the model development was the lack of available data from the Almendares watershed, which is not an uncommon problem and unfortunately is not a problem that is likely to be amended anytime soon. For example, an author from the Olivares-Rieumont et al. (2005) paper informed us that some streamflow records do exist, but are
recorded on paper and stored in filing cabinets in buildings of the Cuban government and are therefore extremely difficult to access (DW Graham, personal communication, September 29, 2011).

However, modeling strategies like the one employed here, which comprehensively account for uncertainty in model equations, model parameters, and model outputs, present a viable option. It is likely that much of the future development and reconstruction work in Cuba will be done by non-Cuban governments, non-profit agencies, and contractors, and our approach may be an attractive one for other analyses until a sufficient database has been developed specific to Cuba. While the topography of the Almendares watershed features notably more elevation changes compared to the relatively flat landscape of South Florida and is an issue that will need to be dealt with better in the future, the other factors such as weather patterns, land use, and land cover are similar enough in the two regions to allow the implementation of data from one region to the other, even across political boundaries. In the big picture, we acknowledge that our approach is not ideal, but feel it is a sufficient first step towards addressing water-quality issues in Cuba and has many promising future applications.

6. Conclusions

The model presented is an attempt to link land uses and water quality in the upper and lower regions of the Almendares River watershed. The model used a GIS platform to divide the watershed into urban and non-urban land uses, and assigned runoff coefficients and EMCs for selected pollutants to each land-use type. Because water-quality data and standards in Cuba were unavailable, the required data and standards were taken from the state of Florida, an approach justified by the highly correlated meteorological patterns between South Florida and Havana. While point-source pollution exists in the watershed, the model did not consider these sources due to a lack of data and a focus on the relationship between land use and water quality. The model only considered pollutant contributions from runoff and surface waters and did not consider groundwater interaction. In neglecting point sources and groundwater, however, the model presents a conservative assessment for analyzing the relationship between land use and water quality in the watershed.

Given the assumptions used to build the model, the results showed that the river junctions with the highest probability of exceeding the water-quality standards are at the intersections of upstream sub-watersheds. This result was found to be true regardless of the land uses within the sub-watersheds or the location of the sub-watersheds within the greater Almendares watershed, indicating that dilution and attenuation combine to reduce pollutant concentrations at downstream river junctions. The junctions of concern had average concentrations near the EMC values assigned to the land uses, indicating that the only way to mitigate the high junction concentrations is to reduce the EMCs by better management of the surface runoff in the upstream sub-watersheds. Attenuation factors over three orders of magnitude were considered, and while the magnitude of the average concentration at some junctions fluctuated, the junctions of concern were the same at all attenuation factors evaluated. Finally, the model was found comparable to an established USGS water-quality model.

This study developed a simple yet effective model to provide a relative assessment of the water quality in the Almendares River watershed in Cuba. The model is a first step in addressing water quality in the Almendares River, and its most significant contribution is the identification of river junctions of concern in the watershed where initial remediation efforts should be directed. The methodology used to develop the model accounts for uncertainty in the model equations, model parameters, and model outputs, and is particularly useful in areas such as Cuba with limited data. The model can be a useful analysis tool in the present and in the future, in both the Almendares River and other parts of Cuba, as more engineering data becomes available and as Cuba addresses the state of its water resources and environment.

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An Epoch-based Metallogenic Scheme for Northern Guyana: A Tool for Mineral Resource Assessment

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Abstract: The need for mineral resource assessments in Guyana has reached a decisive point in view of the country’s Low-carbon Development Strategy (LCDS) within the UN Reduced Emissions from Deforestation and Degradation (REDD+) mechanism. Should the government decide to severely restrict mining in forested lands (which cover over 80% of the country) as part of its LCDS, systematic assessments of the mineral potential of forested lands are needed to provide information on the types and economic value of the undiscovered mineral resources likely to be foregone. An epoch-based metallogenic scheme constitutes an effective first-order tool to help in assessing undiscovered mineral endowment. In this paper, such a scheme is constructed to replace older less satisfactory schemes. The paper reviews existing metallogenic schemes for Guyana to assess their reliability as a tool for mineral resource assessment. A new scheme or conceptual model that uses metallogenic epochs as its building blocks is then proposed for and applied in northern Guyana, where most of the country’s mineral wealth is located. Seven metallogenic epochs are suggested for northern Guyana. Known and possible deposit types are discussed within this framework. The advantages of the new model over the older schemes are discussed. An epoch-based metallogenic scheme is shown to provide more refined insights into Guyana’s mineral potential.

Keywords: Metallogenic epoch, mineral resources assessment, mineral deposit

1. Introduction

The need for regional-scale mineral resource assessments in Guyana has reached a critical point since the recent announcement by the Government of Guyana of its plans to implement a low-carbon development strategy as part of the Reduced Emissions from Deforestation and Degradation (REDD+) mechanism within the United Nations Framework Convention on Climate Change (UNFCCC). As over 80% of the country is forested, a low carbon development strategy involves a commitment of substantial land space. Should the government decide to restrict mining activity as part of its REDD+ strategy, mineral resource assessments would be urgently required to provide information on the number, types and economic value of the mineral resources that are likely to remain untapped.

In assessing mineral potential, metallogenic schemes provide an essential model for the types of deposits that are likely or unlikely to exist in a chosen area. Current models in Guyana are based on lithostratigraphic units, which are distinguished on the basis of only lithic characteristics and stratigraphic position. These models serve as a useful but limited conceptual tool. As shown in this paper, an epoch-based metallogenic scheme constitutes a more perceptive, reliable and encompassing approach. Epoch-based schemes are based on the idea, as pointed out by Goldfarb et al. (2010), that mineralisation is time-bound and related to specific geodynamic events. By themselves, metallogenic schemes of any sort are not designed to quantity potential mineral resources. They, however, constitute an important first-order tool to identify and constrain the types of mineralisation that are geologically permissive in a given region.

2. Geological Sketch of Northern Guyana

Rocks in northern Guyana (north of 4° latitude) were formed during three eras: Paleoproterozoic (the overwhelming majority of units), Mesozoic and Cenozoic. Eight major lithotectonic assemblages are recognised (Delor et al., 2003; Gibbs and Barron, 1990; Norcross et al., 2000; Santos et al., 2003). From the oldest to the youngest, these are:

i) the Paleoproterozoic low-grade volcano-sedimentary sequences, known as the Barama-Mazaruni Supergroup (BMS), with a age of 2.25 -1.9 Ga,

ii) the Paleoproterozoic syn- to post-tectonic granitic intrusions of the Granitoid Complex (2.18-1.96 Ga),

iii) the Paleoproterozoic acid/intermediate volcanics (1.99 - 1.92 Ga) and unmetamorphosed sedimentary sequences of the Burro-Burro Group, (1.99 - 1.92 Ga) and unmetamorphosed sedimentary sequences of the Burro-Burro Group,

iv) the Paleoproterozoic intracratonic sediments of the Granitoid Complex (2.18-1.96 Ga),

v) the Paleoproterozoic continental mafic intrusives of the Avanavero Suite (1782 ± 3 Ma),

vi) the Paleoproterozoic acid-intermediate volcanics (1.99 - 1.92 Ga) and unmetamorphosed sedimentary sequences of the Burro-Burro Group,
vi) the small number of PAPA (post-Avanavero, pre-Apotoe) dykes of basaltic composition (~1330 – 302 Ma),

vii) the Mesozoic continental mafic intrusives of the Apatoe Suite (198 – 189 Ma), and

viii) the Cenozoic coastal sediments.

Figure 1 shows a geological map of Guyana. The most significant tectonic event in northern Guyana was the Trans-Amazonian tectono-thermal episode (2.2-1.9 Ga) encompassing the entire Guiana Shield. Its main manifestations are regional metamorphism, magmatic emplacements, regional deformation, and gold mineralisation (Gibbs and Barron, 1993).

Figure 1. A Geological map of Guyana

3. Assessment of Current Metallogenic Schemes

The most-referenced metallogenic scheme of Guyana is that proposed by Walrond (1980). Walrond identified seven distinct metallogenic provinces based on the demonstrated presence of specific mineralisation within them or on the permissiveness of their geology to host particular mineralisation. His metallogenic provinces are underpinned by large stratigraphic divisions, such as the Barama-Mazaruni Supergroup and the Roraima Supergroup. Within each province, he pinpointed smaller units such as zones and ore districts based on specific deposit types. The work by Walrond remains an important synopsis of mineral potential in the Guiana Shield.

A later work by Voicu (1999) likewise favours a lithostratigraphic-based framework and identifies six metallogenic provinces. As one of his provinces, Voicu delimits a mafic/ultramafic metallogenic province, with the unsatisfactory outcome (typical for such schemes) that rocks of the Avanaver o and Apatoe Suites, which were formed under difference tectonic regimes and over 1.4 billion years apart, are lumped together.

The use of major stratigraphic or lithologic divisions as the basic unit for a metallogenic scheme carries the downside that deposits of different styles, ages of formation, and tectono-magmatic regimes may be placed in one province. As Petrascheck (1965) warns, many regional tectonic units, especially orogens, are formed during several tectonic epochs and, as a result, contain several structural elements of different ages. Recognising that large stratigraphic units (such as a supergroup or complex) can be affected by several tectonic episodes allows for a more refined assessment of the possible mineralisation events within such units. Following Petrascheck’s (1965) advice, this paper recommends that in Guyana the concept of a province be restricted to these tectonic epochs or time intervals.

To illustrate the jeopardy that lithostratigraphic-based metallogenic schemes in Guyana can pose for resource assessment, we point to two examples. The first concerns the empirical evidence that Guyana’s orogenic or greenstone-hosted gold deposits (and, in fact, those in the entire Guiana Shield) are far lower in number, grade and size than those in Canada’s Archean greenstone belts. The historic practice, therefore, of assessing Guyana’s gold potential based mainly on the lithostratigraphic similarities between the greenstone belts of the two countries has produced over-optimistic estimates.

The second example concerns the belief, now widely rejected, that potential exists for paleoplacer uranium mineralisation in the Paleoproterozoic Roraima intracratonic sequence (1873 ± 3 Ma) because of its lithostratigraphic similarities to South Africa’s Archean Witwatersrand deposits and Canada’s Elliot Lake deposits. Such deposits are now considered unlikely to have formed in the oxygen-rich atmosphere that prevailed globally after 2.4 Ga, long before the formation of the younger Roraima sequence (Cox et al., 1993).

The current metallogenic schemes in Guyana, based as they are on large lithostratigraphic and lithodemic components, are therefore imprecise tools for mineral resource assessments.

Given these considerations, this study sees an advantage in using tectono-metallogenic epochs as the building block to construct a metallogenic scheme for Guyana. A metallogenic epoch is commonly interpreted as the time interval that was favourable for the formation of particular economic mineral, or during which a
particular style of mineralisation was most intense, as a result of a major tectonic event or regime. As noted by Goldfarb et al. (2010), there is a temporal pattern to ore deposits, reflecting the complex interplay of geodynamic and other factors. The authors further state that a particular ore deposit type will tend to have a time-bound nature and rocks formed or deformed during a certain time may be permissive for a given deposit type, whereas rocks of less favorable ages would possess less potential.

Using an epoch-based approach, we are first tasked with demarcating periods with distinctive tectonic, magmatic and sedimentary activity and then assessing the potential within each period for particular deposit types. Very few examples of such work exist for other parts of the Guiana shield, one of which by Klien and Rosta-Costa (2011) identifies five metallogenic epochs in the eastern Guiana shield in Brazil.

4. Proposed Epoch-Based Metallogenic Scheme

The successful use of epochs to construct a metallogenic scheme presupposes that geochronological and other data are available to fix the timing and tectonic setting of mineralisation. Little of such data exists for local deposits. Epochs for northern Guyana are therefore mainly delimited based on ore deposit models, crustal-scale temporal patterns of mineralisation, and information from better-studied areas especially in the Guiana shield, such as in studies by Delor et al. (2003).

This study identifies three (3) broad tectono-magmatic periods, each encompassing several metallogenic epochs. The periods are defined relative to the Trans-Amazonian (TA) orogeny, which affected rocks of the Guiana shield between 2.2 and 1.9 Ga. The three periods are: (1) early-Transamazonian (2) late-Transamazonian, and (3) post-Transamazonian. Within these periods, seven metallogenic epochs are proposed for northern Guyana. Epochs are recognised based on tectono-magmatic events and on the actual or potential mineralisation associated with them.

The early-Transamazonian period (2.26-2.08 Ga across the Guiana shield) witnessed the progressive consumption of juvenile oceanic crust during the convergence of the Amazonian and African blocks (Delor et al., 2003a, b). This major subduction process was marked by Tonalite-Trondhjemite-Granodiorite magmatism (TTG) and the formation of volcano-sedimentary greenstone belts across the shield. The belts in Guyana are known as the Barama-Mazaruni Supergroup (BMS). They show a typical greenstone stratigraphic succession with basic/ultrabasic volcanic formations at the bottom, felsic/ intermediate volcanics in the middle, with clastic/ chemical sedimentary rocks at the top (Gibbs and Barron, 1993).

The metallogenic scheme proposed in this paper considers the entire early-TA period as one metallogenic epoch (labeled Epoch 1). In this tectono-magmatic regime, mineralisation is likely to be associated with such lithologies as the felsic submarine volcanics and chemical sediments.

The late-TA period encompasses two epochs in the proposed scheme (Epochs 2 and 3). On the scale of the Guiana shield, Epoch 2 is marked by the formation of granulite-facies metamorphism and emplacement of granites as a result of continental sinistral shearing around 2.0 Ga (Delor et al., 2003a,b). This late TA period is widely acknowledged as the period of most intense epigenetic gold mineralisation in the Guiana Shield (Gibbs and Barron, 1993). Emplacement of gold at Omai (~100 mt Au), Guyana, for example occurred 2001 ± 2 Ma (Norcross et al., 1999).

The other significant metallogenic event related to Epoch 3 in the late TA period relates to the acid magmatism across the Guiana Shield between 2.01-1.96 Ga, interpreted to be subduction-related arc magmatism (Delor et al., 2003a, b). In Guyana, this event is marked by the volcanics, volcaniclastics and comagmatic subvolcanic intrusives of the Iwokrama Formation. Likely mineralisation includes, among others, syngenetic massive sulphide deposit.

The post-TA period in northern Guyana is likewise marked by several significant geologic events. Four metallogenic epochs are proposed (Epochs 4, 5, 6 and 7). Epoch 4 encompasses the events during the Orosirian which lead to the formation of the Roraima Supergroup. These involved the deposition and subsequent uplift of sedimentary sequences in the fault-maintained intracratonic basin (see Santos et al., 2003).

Epoch 5 is associated with the events that led to the intrusion to the emplacement of the large mafic dykes, and sills continental tholeiitic magma belonging to the Avanavero Suite, dated at 1794 ± 4 Ma (Norcross et al., 2000). The Avanavero Suite is assumed to mark a major tectonic event at the scale of the shield (De Roever et al., 2003). Choudhuri et al. (1990) postulate that the voluminous intrusions are related to an abortive attempt at continental rifting. Syngenetic magmatic deposits are possible.

Epoch 6 is related to the tectono-magmatic events associated with the opening of the South Atlantic during the Mesozoic. The associated basic magmatism and block faulting provided conductive conditions for deposit formation.

Epoch 7 marks a period of tectonic quiescence during which erosion and weathering were the dominant agents of deposit formation.

Table 1 provides additional details on the deposit types associated with each epoch in Northern Guyana. While in some cases, mineralisation could be directly linked to an event within an epoch, in other cases the link has not been established.

5. Discussion

The proposed epoch-based metallogenic scheme, through
Table 1: A Proposed Epoch-Based Metallogenic Scheme for North Guyana

<table>
<thead>
<tr>
<th>Periods</th>
<th>Major tectonic and magmatic events</th>
<th>Metallogenic epochs</th>
<th>Main types of mineralisation</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| EARY-TRANSAMAZONIAN | Progressive consumption of juvenile crust with formation of TTG magmatism and volcano-sedimentary greenstone belts. | Epoch 1             | (i) Sedimentary Mn,  
(ii) VMS base metals associated with felsic volcanism, eruptive centres and subvolcanic porphyries.  
(iii) Magmatic Ni-Cu and PGEs, associated with mafic and ultramafic formations of the BMS.  
(iv) Algoma Fe/volcanogenic magnetite | (i) Confirmed. Mn mineralisation, in the North-West of Guyana.  
(ii) No unambiguous VMS mineralisation found.  
(iii) Confirmed. Occurrences and soil anomalies in the BMS, e.g., PGE at Karemembu.  
(iv) Confirmed occurrence in the upper Pomeroon. |
| LATE-TRANSAMAZONIAN | Subduction-related acid magmatism, represented by the Iwokrama formation in northern Guyana. | Epoch 2             | (i) Orogenic Au, associated with late orogenic metamorphic fluids.  
(ii) Intrusion-related Au, genetically associated with felsic intrusives.  
(iii) Intrusive-related uranium mineralisation.  
(iv) Albitite-hosted uranium mineralisation. | (i) Confirmed. Hundreds of Au occurrences and deposits exploited.  
(ii) Eagle Mt is a possible example.  
(iii) Speculative.  
| POST-TRANSAMAZONIAN | Block faulting, deposition and uplift associated with the formation of the Roraima Supergroup. | Epoch 3             | (i) VMS deposits in felsic volcanics | (i) Speculative |
|                | Crustal extension as a result of failed continental rifting, associated with the emplacement of the Avanavero suite. | Epoch 5             | (i) Magmatic Ni-Cu and PGEs associated with differentiated basalts of the Avanavero Suite. | (i) Exploration results unfavorable to date. |
|                | Precursor basic magmatism and block faulting in connection with opening of the South Atlantic (the South Atlantic Event -approx 200 Ma). | Epoch 6             | (i) Magmatic Ni-Cu and PGEs associated with differentiated basalts of the Apatoe Suite. | (i) Speculative. |
|                | Tectonothermal quiescence.                                                                         | Epoch 7             | (i) Supergene/lateritic Mn.  
(ii) Supergene bauxite.  
(iii) Lateritic Ni.  
(iv) Modern placers of diamond and Au | (i) Confirmed. Measured resources.  
(ii) Confirmed. Proven reserves.  
(iii) Confirmed. Ni anomalies.  
(iv) Confirmed. |

S. Lowe: An Epoch-based Metallogenic Scheme for Northern Guyana: A Tool for Mineral Resource Assessment

Tentative and vague in several regards, provides a more reliable and useful model for the assessment of mineral potential in northern Guyana. Several examples illustrate this:

i) the relative potential for magmatic Ni-Cu sulphide deposits of the three main mafic/ultramafic complexes in northern Guyana (the mafic/ultramafic metavolcanics of the Rhyacian greenstone belts of Epoch 1, the sills and dykes of the Statherian Avanavero Suite of Epoch 5, and the dykes of the Mesozoic Apatoe Suite of Epoch 6) can be assessed based on the presence of a felsic crust (the common source of sulfur) at the time of their formation. On this criterion alone, the absence of crustal material during the formation of the Guiana greenstone belts makes...
the metavolcanics less prospective;

ii) the sedimentary manganese deposits (Epoch 1) and supergene/lateritic manganese deposits (Epoch 7), while associated with the same lithostratigraphic unit, are placed in different metallogenic epochs, separated by over two billions years of geologic time. The older deposit is a primary sedimentary deposit, while the second is a secondary deposit formed from the weathering of the first. Current exploration in Guyana focuses on the younger secondary deposits. The older primary deposits, however, constitute a potential resource requiring a separate assessment based on the depositional environments prevalent in the early Transamazonian period;

iii) the Roraima Supergroup as a single lithostratigraphic unit contains potential and discovered mineralisation of different styles and epochs. These include quartz-pebble paleoplacer gold mineralisation (Epoch 4), the unconformity-type uranium deposit (Epoch 4 or later) and diamondiferous kimberlites. To treat the basin as one metallogenic province, as done by previous workers, is an inappropriate model to assess the several genetic styles involved;

iv) the epoch-based approach allows the four classes of uranium mineralisation known or likely in northern Guyana, (the unconformity-type, the intrusive type, the albitite-hosted type and the conglomeratic paleoplacer type) to be placed in a proper temporal sequence based on their ages of formation and tectonic settings. Given that uranium mineralisation occurred during several epochs in northern Guyana, the potential for economic deposits should be considered significant;

v) the fact that volcanogenic massive sulphide (VMS) deposits have been found in great abundance in the Canadian Shield but to an insignificant extent in the Guiana Shield has provoked much debate (as well as frustration) in Guyana. From an epoch-based metallogenic perspective, however, the Paleoproterozoic era, the age of the Guyana’s VMS-permissive greenstone belts, is considered one of the six major global periods of VMS formation (Franklin et al., 2005). Lack of known deposits in Guyana, therefore, may not be due to unfavorable geodynamic conditions operating in the crust at the time. This view bolsters the argument that past unsuccessful exploration for VMS deposits was due to poor exploration designs;

vi) the epoch-based approach facilitates an assessment of the impact on deposit formation of tectonic and other events in the Guiana shield, such as the K’mudiku Episode (1.3-1.2 Ga), that are not associated with the emplacement of new material in the upper crust and, as such, with no specific lithostratigraphic units. Such events may, however, cause the reactivation of mineralisation processes and structures as well as the formation of deposits of metamorphic origin.

6. Conclusion

As more geochronological, tectonic and mineral exploration data become available for the Guiana Shield and similar areas worldwide, the epoch-based metallogenic model can become a more powerful tool to define temporal patterns of mineralisation in Guyana. As such, the continuation of the recent government project that involved the radiometric dating of rocks in southern and central Guyana has begun to provide invaluable data that can enhance an epoch-based scheme. Land-use decisions (such as the REDD initiative) can then be made on a more informed basis than at present.

References:


Klien, E.L. and Rosa-Costa, L.T. (2011), Metallogenesis of Eastern Guiana Shield in Brazil, (s.n.)


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Sherwood Lowe is a lecturer in mineral exploration at the University of Guyana. Prior to working at UG, Mr. Lowe worked as a project geologist at the Guyana Geology and Mines Commission from 1990 to 1995. His current research interest is in mineral resource assessment. He recently completed a report on the mineral resources assessment of northern Guyana for ten deposit types, using qualitative and quantitative techniques. The current paper is extracted and modified from that work.
Petrophysical and Microhardness Characterisation of the Sans Souci Formation, Trinidad

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\textbf{Abstract:} Since 1907, the Sans Souci Formation, the only igneous outcrop in Trinidad, has been investigated using scientific procedures such as lithology, stratigraphy, petrology, paleomagnetism, microscopic analysis and mineralogy. The approach taken in this work revolved around mineralogical, topographical, elemental and microhardness distribution characteristics using various laboratory analysis techniques, including x-ray diffraction (XRD), scanning electron microscopy, physical properties characterisation and vickers hardness methods. This is an attempt at quantitatively characterising the mineralogy as well as determining the elemental distribution within the rocks of the Formation. The results are expected to contribute to existing knowledge with respect to the petrophysical and microhardness characterisation of the Sans Souci Formation. Qualitative and quantitative XRD analyses of three (3) outcrop samples studied established that the minerals calcite, chlorite and albite featured predominantly in the Sans Souci Formation. Physical characteristics such as apparent porosity, bulk density and water absorption were also determined and their values ranged 0.91-1.97\%, 0.58-1.29\% and 1.50-1.69 g cm\textsuperscript{-3}, respectively. The average Vickers Hardness value for sample SS3 was determined to be 833.9.

\textbf{Keywords:} Petrophysics; microhardness; mineralogy; Sans Souci; Scanning Electron Microscopy

1. Introduction

Trinidad is the southernmost of the West Indian islands. The Sans Souci Formation is located in the eastern region of the Northern Range and is the only igneous outcrop found in Trinidad (Cruz et al., 2007; Donovan, 1994). As early as 1907 this small outcrop, formerly known as the Sans Souci Volcanic Formation, was described in terms of lithology, geology, petrology, mineralogy and microscopy. Cunningham-Craig (1907) classified it as an epidiorite sill. Waring (1926) used microscopic analysis to establish that the igneous rocks were a combination of basaltic tuff, granophyre and diabase. Maxwell (1948) employed the same technique as Waring (1926) and obtained similar results, in that the igneous rocks were a stock of andesitic composition. Barr (1963) described the rocks as dense, lithified, dark-green to grey-green, generally fine grained and poorly sorted pyroclastic material. Wedge and Macdonald (1985) discontinued the use of the name Sans Souci Volcanic Formation and formally used Sans Souci Formation after they determined the major and trace elements and petrophysically described the chemical alteration of the rocks. Frey, Saunders and Schwander (1988) used x-ray powder diffraction to determine the mineralogy of the rock sample, but only qualitatively.

In terms of a petrophysical description of the Sans Souci Formation, the works cited above represent the most significant researches thus far. In this present study, a non-invasive laboratory approach which involved a combination of petrophysical techniques to characterise the rock samples was adopted. These included x-ray diffraction (XRD), scanning electron microscopy (SEM), physical characterisation and vickers hardness methods. With the application of these techniques, these outcrop samples can be qualitatively and quantitatively characterised in terms of their mineralogy and elemental composition as well as microstructurally defined. This work serves to augment the paucity of research done with respect to the petrophysical and microhardness characterisation of the Sans Souci Formation.

Therefore, the main objective of this research was to give a more detailed petrophysical characterisation of the igneous rocks of the Formation using a combination of advanced analytical techniques now available.

2. Materials and Methods

2.1 Sampling Technique

Samples were taken at the type section of the outcrop close to the Old Sans Souci Fishing Depot (see Figure 1).
Fresh unweathered samples were preferred in order to avoid probable misleading results should weathered samples be used. The samples were chiselled out of the rock mass beneath the regolith layer.

**2.2 Laboratory Methods**

**X-ray powder diffraction**

XRD and mineralogical characterisation of the rock samples was done using Cu Kα radiation in a Bruker 5005D x-ray diffractometer. Samples from the bulk rocks were ground to a particle size of less than 500 µm, and analysed over the 2-theta range 3º to 40º (Jenkins and Snyder, 1996; Knorr and Bruker, 2008; Pecharsky and Zavalij, 2009; Szponder and Trybalski, 2010). In conjunction with the qualitative profiles obtained, the TOPAS software based on the Rietveld quantitative phase analysis was used to generate quantitative data. This is a widely used and reliable quantitative phase analysis technique widely employed in both research and industrial purposes (Chalmers, Ross and Bustin, 2012; University of Cambridge, 2012).

**Scanning electron microscope**

Fractured sections from the bulk rocks were gold coated and imaged in a Philips 500 electron microscope operated at 20 kV. Energy Dispersive X-ray Analysis (EDXA) elemental mapping was also done using the microscope together with the EDAX Genesis elemental analyser (Goldstein et al., 2003).

**Physical characterisation methods**

The water displacement method based on the Archimedes principle was used to determine the apparent porosity, bulk density and water absorption of the samples (Yavuz, Demirdag and Caran, 2010). The method involved obtaining a dry weight $W_d$ and a wet weight $W_w$ after the open pores were saturated with water under vacuum. Subsequently, a suspended weight $W_s$ was also obtained (ASTM, 2006; Siegesmund and Durrast, 2011). These weights were used to calculate the various physical property parameters according to:

$$\text{Apparent Porosity} = \frac{W_w - W_d}{W_w} \times 100\%$$  (1)

$$\text{Water Absorption} = \frac{W_d - W_w}{W_w} \times 100\%$$  (2), and

$$\text{Bulk Density} = \frac{W_d}{W_d - W_s} \text{ g cm}^{-3}$$  (3)

In each sample twelve (12) replicates were used to calculate the standard deviation.

**Vicker’s Hardness**

Samples from the Formation studied in this research were set in resin, ground and polished, then mounted and tested in the Buehler, IndentaMet 1100 Series MicroIndentation Hardness Testers. This equipment was used to determine the Vickers Hardness Values for the rock samples. A load of 300 grams was used and a dwell time of 8 seconds was applied to the resin set samples.

All three samples taken from the Sans Souci Formation were prepared to determine the Vickers Hardness, however SS1 and SS2 samples could not be used due to the poor nature of the samples such that no determinations of Vickers Hardness could have been made. In addition to obtaining the hardness number, the indentation response of the sample was observed and imaged using the camera of the instrument interfaced with a computer.

### 3. Discussions

Table 1 shows the general description of the Sans Souci samples analysed. Generally, all three samples were similar in appearance, with the exception that SS2 displayed areas of purple and magenta hues.

<table>
<thead>
<tr>
<th>Rock Classification</th>
<th>Sample</th>
<th>General Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metabasalt</td>
<td>SS1</td>
<td>Black, dark grey, angular and very dense in appearance and texture</td>
</tr>
<tr>
<td>Metagabbro</td>
<td>SS2</td>
<td>Black, grey, dark brown, purple/magenta appearance, angular and very dense</td>
</tr>
<tr>
<td>Metabasalt</td>
<td>SS3</td>
<td>Black, grey, angular and very dense in appearance</td>
</tr>
</tbody>
</table>

**On X-ray diffraction**

Figure 2 shows normalised XRD profiles for SS1, SS2 and SS3. As can be seen, quartz, chlorite, calcite and albite were the most prominent minerals detected in the SS1 and SS2 samples. In the SS3 sample, chlorite and calcite predominated. Quantitatively, Table 2 reveals that in fact SS3 was comprised mostly of calcite and chlorite and to a lesser extent albite. On the other hand, the constituents of SS1 and SS2 were mostly calcite, chlorite and albite. Qualitatively, these minerals detected in the SS1, SS2 and SS3 samples were basically the same.
reported by Frey, Saunders and Schwander (1988) for their sampling site in the Sans Souci Formation.

higher magnification imaging in the vicinity of the quartz veins (Figure 3(b)), suggests that there may be some degree of vertical layering in the calcite/chlorite/albite intermix. In yet another selected region of the same sample (Figure 3(c)), angular quartz grains (left) can be seen embedded in the intermix.

On scanning electron microscopy

Table 2 shows the quantitative mineralogical values obtained for rock samples. Figure 3(a) shows a SEM micrograph of a selected area of horizontally stacked, bedded intermixed calcite/chlorite/albite permeated by transverse quartz veins in the SS1 sample in which the combined calcite/chlorite content amounted to some 84%.

Table 2. The quantitative mineralogical values obtained for rock samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Quartz (%)</th>
<th>Calcite (%)</th>
<th>Chlorite (%)</th>
<th>Albite (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS1</td>
<td>3.79</td>
<td>63.12</td>
<td>20.63</td>
<td>12.46</td>
</tr>
<tr>
<td>SS2</td>
<td>4.11</td>
<td>17.08</td>
<td>31.78</td>
<td>47.02</td>
</tr>
<tr>
<td>SS3</td>
<td>0.48</td>
<td>76.05</td>
<td>14.69</td>
<td>8.78</td>
</tr>
</tbody>
</table>

Figure 2. Normalised XRD profiles for samples SS1, SS2 and SS3

Figure 3(a). A SEM micrograph of a selected area of the SS1 sample

Figure 3(b). Higher magnification imaging in the vicinity of the quartz veins

Figure 3(c). Higher magnification imaging in the vicinity of the angular quartz grains

To highlight the variability of the microstructure of the samples, Figure 4(a) shows a selected area of fine particulate calcite in the sample SS3. High magnification imaging (Figure 4(b)) further reveals a honeycomb-like texture to the particles.

Figure 5 shows a selected region of the SS1 sample with the corresponding elemental maps shown in Figure 6. Consistent with quartz, calcite, chlorite and albite being the major constituents (see Table 2), areas rich in, for example Al (Figure 6(a)), Si (Figure 6(b)) and Ca (Figure 6(d)) are clearly identifiable. Further, in addition to Fe and Ti, trace amounts of Na, V, Mn, Co, B were also detected and confirmed on the basis of the EDXA spectrum (see Figure 7) obtained from the same field of view of the sample.
Table 3. Physical properties of the samples

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Apparent Porosity/ %</th>
<th>Bulk Density/ g cm$^{-3}$</th>
<th>Water Absorption/ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS1</td>
<td>1.44 ± 0.39</td>
<td>1.56 ± 0.01</td>
<td>0.92 ± 0.25</td>
</tr>
<tr>
<td>SS2</td>
<td>1.97 ± 0.46</td>
<td>1.69 ± 0.17</td>
<td>1.29 ± 0.30</td>
</tr>
<tr>
<td>SS3</td>
<td>0.91 ± 0.23</td>
<td>1.50 ± 0.10</td>
<td>0.58 ± 0.15</td>
</tr>
</tbody>
</table>

On Physical Properties

Table 3 shows the apparent porosity, bulk density and water absorption of the samples. For all of the samples the apparent porosity and the water absorption were low.

Vicker’s Hardness

From the results shown in Table 4, the average Vickers Hardness value for sample SS3, was determined to be 833.9. The response of the rock to indentation is shown in Figure 8. Lateral cracks and lateral chipping can be seen around the indentation. Due to the indentation, the areas around the indentation appear to be pushed upwards, indicated by shiny appearances around the square based pyramid indent. However, this behaviour seen for the SS3 samples relates to that of a typical brittle material.
4. Conclusions

The Sans Souci Formation was characterised petrophysically and microstructurally defined using a combination of analytical techniques which included X-Ray Diffraction, Scanning Electron Microscopy, Physical Characterisation and Vickers Hardness Methods. Physically, the rocks of the Formation are hard and dense and of low porosity with, at a microscopic level, considerable variability in microstructure.

The results of the mineralogical analysis for the type section studied, revealed that the rocks are comprised principally of calcite, chlorite, quartz and albite. Spatially, however, there is, in terms of composition, a high degree of variability to their relative proportions. The empirical hardness value determined for this Formation was relative to the micro hardness scale. The Sans Souci Formation is now microstructurally characterised. The originality of this work lies therein the analytical techniques used to microstructurally characterise the Sans Souci Formation, and the properties analysed can be further used for civil engineering purposes.

References:


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Microphone Placement for Tenor Pan Sound Recording: New Recommendations Based on Recent Research

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Abstract: The placement of recording microphones used for live recording, studio recording or sound reinforcement of a tenor steelpan is revisited using new research findings on the soundfield of the instrument. The new results were obtained using a technique called Nearfield Acoustical Holography (NAH). An analysis of the existing microphone techniques and the recommendations for new positions based on the soundfield information is made.

Keywords: Acoustics, Nearfield Acoustical Holography, Sound Intensity

1. Introduction

The placement of microphones for recording or reinforcing the sound of any musical instrument, has a significant effect on creating the overall tonal quality intended by the composer, performer, or recording engineer (Bartlett, 2010). The positioning of recording microphones has been largely a learnt art, requiring experimentation, trial and error, a keen ear and engineering know how. In the specific case of the tenor steelpan, the placement of microphones has been ad hoc, often dictated by stage clutter, convenience and logistics rather than being based on scientific evidence (Copeland, 2002).

A previous paper on the subject of microphone placement (Copeland, 2002) specifically advised where to not place the microphones based on the then available information. New research findings on the sound radiation characteristics of the tenor steel pan can provide much needed scientific guidance as to where microphones can be placed in order to better record or reinforce the full tonal range of this instrument. This paper will look at this new data, how it was obtained recommend microphone placement positions based on this new evidence.

2. Instrument Studied: The Kelman Low Tenor Steelpan

The Caribbean steelpan is a tuned idiophone whose sound is produced by the physical impact of playing sticks on the notes (Murr et al., 2004). The steelpan instrument family has a note range of E₁ (41.2 Hz) to G₆ (1587.98 Hz) and if the contributions of partials are included, has a frequency range comparable to that of a grand piano (Copeland, 2005).

Individual instruments contain from three (3) notes, in the case of a single bass steelpan to thirty-two (32) notes arranged in three concentric rings in the case of a soprano tenor pan. The particular instrument being referred to in this paper is a twenty-nine (29) note, low C tenor designed, manufactured and tuned by Bertrand Kelman, an acknowledged maker and tuner in the steelpan fraternity. This instrument has a diameter of 0.585m, a skirt length of 0.18m and a bowl depth of 0.225m.

3. Measuring the Soundfield of the Kelman Tenor Steelpan

Scientifically supported placement of recording microphones requires knowledge of how the instrument behaves acoustically, specifically, from where does it generate its sound energy and in which directions does the sound energy propagate. Only when this information is known can the optimum location for the placement of microphones be decided. This acoustic behaviour is obtained by studying the sound (acoustic) intensity of the instrument.

The sound intensity, I(r), is a vector which is a measure of the magnitude and direction of the flow of sound energy. It is defined as the net flow of sound energy through a unit area in a direction perpendicular (normal) to the area (Fahy, 1997). At some field position r, I(r) can be described in terms of the complex pressure p(r) and particle velocity u(r) at that position as:
\[ I(r) = \frac{1}{2} p(r) u'(r) \]  

(1)

The components of \( u(r) \) are themselves related to the pressure, \( p(r) \), according to Euler's equation 2:

\[ u(r) = -j\frac{\partial}{\partial \rho_0} p(r) \]  

(2)

where \( \omega \) is the angular frequency of the source in rad/s and \( \rho_0 \) is the density of air in kg/m³. Because of this relationship, it is possible to determine both components of \( I(r) \) using a pair of calibrated, precisely spaced microphones, to measure \( p(r) \), calculate \( \nabla p(r) \) and then \( u(r) \). This technique has been extensively documented, for example by Fahy (1997) and has been used in the measurement of the soundfield of the steelpan by Copeland (2005).

An alternative method for obtaining the components of \( I(r) \), without the need for the specially spaced microphones, is through the use of Planar Nearfield Acoustical Holography or NAH. Planar NAH is another well documented method (Maynard et al., 1985, Rowell and Oldham 1995), whereby the acoustic energy emitted by a source can be reconstructed in three dimensions from a single set of measurements of the complex pressure taken on a measurement surface close to the source. In Cartesian coordinates, for a source oriented in the xy plane for example, the measurement surface, called the hologram or measurement plane, is located at some distance \( z = z_0 \) from the source plane at \( z = z_s \). The distance \( z_s - z_0 \) must lie within what is termed the acoustic nearfield of the source, which typically taken as being within one eighth of the wavelength of the acoustic signal being processed (Williams, 1999), in order to capture essential acoustic information which decays rapidly as the distance from the source increases. Note that the source plane may or may not coincide with the actual source surface and is entirely dependent on the geometry of the source. Figure 1 illustrates the geometry of Planar NAH.

Planar NAH is described generally by a two dimensional convolution of the measured complex sound pressure \( p(x,y,z_0) \) and the normal derivative of a function, \( g \), as follows (Maynard et al., 1985):

\[ \Psi(x,y,z) = \int \int \int_{-\infty}^{\infty} p(x_0, y_0, z_0) \frac{\partial g}{\partial z}(x-x_0, y-y_0, z-z_0) dx_0 dy_0 \]  

(3)

In Eq.3, \( \Psi(x, y, z) \) can refer to either the pressure \( p(x, y, z) \) or the particle velocity \( u(x, y, z) \). The variable \( g \), is referred to as the free space Green’s Function (Kinsler et al., 2000) and is the impulse response of the sound propagating medium. For a field position \( r \), \( g(r) \) and its normal derivative are given by:

\[ g(r) = \frac{e^{jkz}}{4\pi|r|} \]  

(4)

\[ \frac{\partial g}{\partial z} = -\frac{z(1-jk r)e^{ikr}}{2\pi r^2} \]  

(5)

The practical implementation of planar NAH uses two (2) sampled, Fourier transformed versions of Eq.3, which facilitate (i) the evaluation of the convolution integral; and (ii) the calculation of both the pressure and particle velocity information. These versions are given in equations (6a) and (6b) respectively as:

\[ p(x,y,z) = \mathcal{F}_x^{-1} \mathcal{F}_y^{-1} \mathcal{F}_z \left[ p(x,y,z_0) \right] \times G_p(k_x, k_y, z-z_0) \]  

(6a)

\[ u(x,y,z) = \mathcal{F}_x^{-1} \mathcal{F}_y^{-1} \mathcal{F}_z \left[ p(x,y,z_0) \right] \times G_v(k_x, k_y, z-z_0) \]  

(6b)

The following are the important features of Eq.6a and Eq.6b:

1) In both equations, \( \mathcal{F}_x \mathcal{F}_y \) refers to a two dimensional \( k \)-space Fourier Transform defined as (Muddeen, 2012):

\[ \mathcal{F}_x \mathcal{F}_y = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x,y)e^{-i(k_x x)} e^{-i(k_y y)} dx dy \]  

(7)

2) \( G_p(k_x, k_y, z-z_0) \) and \( G_v(k_x, k_y, z-z_0) \) the two-dimensional \( k \)-space Fourier transformed free-space Green's Function for pressure and particle velocity. In planar NAH, \( G_p(k_x, k_y, z-z_0) \) is referred to as the pressure propagator function and \( G_v(k_x, k_y, z-z_0) \) as the velocity propagator function (Williams, 1999). They are defined respectively as:

\[ G_p(k_x, k_y, z-z_0) = e^{ikz} \]  

(8)

\[ G_v(k_x, k_y, z-z_0) = \frac{k_z}{\rho_0 c_k} e^{ikz} \]  

(9)

The derivation of (9) according to Williams (1999) incorporates Euler's Equation 2, so that both of the components that are required to calculate \( I(r) \) can be deduced from Equations 6a and 6b. The complete
derivation of Eq.3 together with a discussion of the practical considerations, limitations and errors can be found in Muddeen (2012) and is based on the original derivation given in Maynard et al. (1985).

In summary, therefore, the usefulness and advantage of the NAH approach is that with a single set of complex pressure measurements, the velocity vector and hence the AI and RI vectors can be derived for the space above the source.

### 3.1 Sound Intensity Components

I(r) has two components – an active component which indicates how the acoustic energy propagates to the farfield and a reactive component which shows how the acoustic energy circulates around the source and also indicates the acoustic energy sources and sinks of the source. The direction of the active component vectors, called the Active Intensity (AI), is normal to surfaces of constant phase. The direction of the reactive component vectors, called the Reactive Intensity (RI), is normal to surfaces of constant pressure (that is, the soundfield wavefronts).

### 3.2 Complex pressure measurement

Planar NAH requires the use of complex pressure measurements, that is, pressure measurements whose magnitude and phase with respect to a reference source, are known. This information is obtained from the auto spectrum and the cross-spectrum of two sets of pressure data according to a method used by Blacodon et al. (1987) as follows.

If the Fourier Transform of the reference pressure at spatial position \( r_0 \), is denoted by \( P_{ref}(r_0) \), and the Fourier Transform of the measured pressure at spatial position \( r \) is denoted by \( P(r) \), then the pressure magnitude \( |P(r)| \) can be derived from:

\[
|P(r)| = \sqrt{P(r) \cdot P(r)^\ast}
\]  

(10)

The signal phase \( \phi_{xy} \), can be calculated from the angle of the cross spectrum according to the following equations:

\[
S_{xy} = |P(r)\cdot P_{ref}(r_0)^\ast| \cdot \phi_{xy}
\]  

(11)

where

\[
\phi_{xy} = \angle P(r) - \angle P_{ref}(r_0)
\]  

(12)

### 4. Experimental Setup

The experimental setup used is completely described in Muddeen (2012) and is summarised here. The complex sound pressure level (SPL) around the Kelman tenor pan was measured in six (6) planes completely enclosing it. The horizontal source planes were \( x-y \) planes in the global coordinates, with the top source plane taken as being that one through the rim of the instrument and the bottom source planes, the source plane as being that one through the lowest point of the bowl of the instrument.

The horizontal measurement (hologram) planes were located 0.05m above and below these locations respectively. The four (4) vertical source planes were \( y-z \) and \( x-z \) planes in the global coordinates in contact with the rim of the instrument as shown in Figure 1(a). The measurement planes were located 0.05 m away from these planes (Muddeen, 2012).

The measurements for this study were taken under controlled conditions in the anechoic chamber of the Physics Department at Northern Illinois University, DeKalb, Illinois. The test instrument was supported by a special frame which clamped the instrument under test by its rim and facilitated rotation of the steelpan in a vertical plane and locking at any desired inclination. The frame was designed by the author and fabricated by the workshop of the NIU Physics Department.

There are several accepted note excitation techniques available for the steelpan, which have been discussed in the literature, for example by Copeland (2005), Rossing and Hansen (2002, 2004) and Muddeen (2012). This experiment used an electromagnetic excitation system for exciting the notes for which a detailed description and photograph of the system used can be seen in Figure 3 in the paper by Copeland (2005). The pressure data was acquired using two calibrated sound level meters (SLMs) interfaced to a 12-bit ADC212 100 MHz PICO scope configured as a dual channel, computer controlled datalogger.

### 5. Observations on the Sound Radiation of the Tenor Pan

Figure 2 shows a typical result obtained for the AI of the tenor pan using planar NAH. This image was produced for a frequency of 286 Hz in the low frequency range of the instrument.

![Figure 2. Typical low frequency active intensity behaviour of Kelman Tenor Pan](image-url)
In this view, the AI vectors are depicted as cones in the $xz$ plane and show the direction of the flow of acoustic energy, while the colour indicates the time averaged AI level in dB. A complete set of results showing the SPL, AI and RI behaviour of the tenor pan in detail, including some three dimensional isosurface plots, can be found in Muddeen (2011). In addition, more information on the sound radiation from caribbean steelpans and the use of sound intensity can be found in Copeland et al. (2005).

For the purpose of identifying locations for the placement of microphones, Figure 3 summarises the time averaged Active Intensity (AI) levels in two planes: one through the test note; and one transverse to the test note. This orientation is illustrated in Figure 2.

The following conclusions can be drawn from these figures:

1. The sound radiation patterns of the tenor pan vary considerably with frequency;
2. In general, the tenor steelpan projects its sound upwards and downwards, with a small forward directivity in a somewhat similar fashion to an unbaffled loudspeaker;
3. At low frequencies, the tenor pan radiates very uniformly in an omnidirectional pattern above the note playing surface of the instrument, as shown in Figure 4. In addition, the instrument radiates more sound energy above as compared to below;
4. As the frequency increases, very distinct regions of high sound intensity become apparent. At mid frequencies, shown in Figure 5, there are clearly two (2) zones of high AI level above the instrument and one below;
5. At high frequencies, shown in Figure 6, there are four (4) zones of high AI level above the instrument and two (2) zones below;
6. For both mid and high frequencies, in contrast to the low frequency behaviour, the instrument radiates more powerfully below than above the note playing surface; and
7. The instrument does not radiate efficiently or significantly in a horizontal direction in the region of the skirt.

Note: The location of the test note is shown by the red star.
(a) represents a plane through the test note and
(b) represents a plane transverse to the test note.

**Figure 3.** Orientation of the observation planes

**Figure 4.** Frequency response at 287 Hz

**Figure 5.** Frequency response at 585 Hz

**Figure 6.** Frequency response at 885 Hz
6. Recommendations
The immediate conclusion with respect to microphone placement that can be drawn from these new results is that for proper recording of the tenor steelpan, a single microphone is not optimum, especially one located in front of the pan. Interestingly, Shure (2009) recommends a single microphone located 4” above the instrument, for the tenor pan. Shure (2009) does not specify where exactly above the pan, but are presumably referring to the centre of the bowl.

From the acoustic information now available (shown in Figures 4, 5 and 6), this position is not adequate for three contradictory reasons:
1. The intensity of the sound radiation over the centre of the instrument (bowl) decreases rapidly as the frequency rises as can be seen in Figures 4 and 5. A microphone placed over the centre of the bowl would be picking up essentially the low frequency radiation of the pan;
2. The tenor pan is a percussion instrument played by striking the notes with a rubber wrapped, wooden or aluminum stick. Close microphone placement (‘close miking’), would detect a substantial amount of the impact noise of the stick on the metal note surface which would severely colour the sound. The effect of close miking on tonal quality is discussed by Bartlett (2010), and his recommendations are made without the scientific support of the intensity measurements we now have available for the tenor pan; and
3. The steelpan is a loud instrument under most playing conditions. Sound measurements taken inside a playing orchestra have recorded SPL values of over 105dBA (Juman, 2004) in the centre of the front line pans, which comprise mostly tenor pans. This can create problems for close miking, for example amplitude clipped input signals and unwanted distortion unless the inputs are attenuated or a microphone selected especially to handle high SPLs is used.

Compensating for these scenarios electronically is not particularly easy since adjustment for one set of factors invariably makes another situation worse. For example in scenario (1) above, it is possible to boost the middle and high frequencies to compensate to some degree, but, based on the results obtained, significant gain would have to be used. However, this contradicts the requirement from scenario (3) that the inputs be attenuated to avoid clipping. In addition, the presence of impact noise from scenario (2) would reduce the SNR considerably if large gains are used, leading to the implementation of even more post recording signal conditioning and loss of tonal fidelity.

Observation (7) in Section 5 above has significant implications to the location of the audience in live performances. Because of the low sound radiation horizontally, an audience located at the same level as the performer or performers, will not hear the instrument as well as the listeners located in an elevated position. Ironically, for paid concerts, it is normal to have the highest priced seats located immediately in front of the performers, so that the costliest seats could actually experience the lowest audio quality.

Based on these recent sound field findings, the authors therefore make the following recommendations for the placement of microphones for the recording of the tenor pan for live or studio performances. The optimum recommendations use a combination of one dynamic microphone and one boundary (pressure zone) microphone and depend on whether or not the instrument is being played on an acoustically reflective (hard) surface or an acoustically absorptive (soft) surface.

6.1 Classification of acoustical reflectivity of surfaces
The acoustic reflection characteristics of a performing surface, for example a floor, can be ascertained by examining the sound absorption coefficient of the playing surface. The sound absorption coefficient, $\alpha$, of a material can be calculated from:

$$\alpha = \frac{I_{\text{absorbed}}}{I_{\text{incident}}}$$

In Eq.13, $I_{\text{absorbed}}$ is the intensity of sound absorbed by the material and $I_{\text{incident}}$ is the incident intensity of sound on the particular material, both in units of Watts/m$^2$. The method for the determination of $\alpha$ has been standardised in International Standard, ISO 354 (2003) and tables of sound absorption coefficient data for various materials are available, for example in Crocker (2000), so that a scientific determination of the type of performing surface can be made. It is also important to note that sound absorption coefficient values are frequency dependent.

For example using standard values from Crocker (2000), a hard reflecting surface is one where the coefficient of absorption of sound is low, <0.02, at the frequencies of interest. Concrete floors, terrazzo, ceramic and porcelain tile fall into this category with coefficients of <=0.02 up to 4kHz. An acoustically absorbent surface is one where the coefficient of absorption of sound is high, >=0.5, at the frequencies of interest. Carpet, wood, artificial surfaces and grass as examples fall into this category with coefficients of >=0.5 up to 4kHz.

6.2 Two Microphone Techniques
(a) Performance on a hard reflecting surface
For low frequencies, a cardioid, supercardioid or hypercardioid dynamic microphone mounted 0.5m over the centre of the instrument. There is some flexibility allowed in the lateral position because of the uniform low frequency radiation pattern of the tenor pan. For the middle and higher frequencies, a cardioid boundary (pressure zone) microphone located vertically below the
front skirt. This configuration, shown in Figure 7, would be able to pick up a reasonably consistent level even when the pan moves during playing. Both top and bottom inputs would be equalised so as to create the desired tonal quality. Note that the boundary mike must not be used if the floor is being used for other performances for example dancing, accompanying the pan, since it would pick up the vibrations of the stage.

(b) Performance on a soft reflecting surface
For low frequencies, a cardioid, supercardioid or hypercardioid dynamic microphone mounted 0.5m over the centre of the instrument as before. For the middle and higher frequencies, there are two possibilities listed in order of preference. The configuration shown in Figure 8(a) uses a cardioid, supercardioid or hypercardioid dynamic microphone located 0.5m vertically below the front skirt (Note that the lower microphone should be kept vertical to minimise reception of any residual floor reflections).

The second, less preferred configuration is shown in Figure 8(b) and uses a cardioid, supercardioid or hypercardioid dynamic microphone located 0.5m vertically above the front skirt. This configuration would require more equalisation than the first recommendation (see Figure 9(a)), because of the lower levels of mid and high frequency partials above the instrument. It will also be more susceptible to varying levels due to instrument movement.

6.3 Single Microphone Techniques
Situations will arise where, for a variety of reasons, two microphones cannot be used or are impractical. Under these circumstances, the following single microphone positions are recommended:

(a) Performance on a hard reflecting surface
Place a cardioid boundary (pressure zone) microphone vertically below the front skirt. This position, shown in Figure 9, would require boosting of the low frequencies since, according to the evidence presented, the tenor pan radiates its higher frequency partials more efficiently below the instrument. Again, this location would be able to pick up a reasonably consistent level even when the pan moves during playing.

(b) Performance on a soft reflecting surface
Two configurations are recommended in order of preference. The first, shown in Figure 10(a) uses a cardioid, supercardioid or hypercardioid dynamic microphone located 0.5m vertically below the front skirt. Note that the microphone should be kept vertical to
minimise reception of any residual floor reflections. The second configuration, shown in Figure 10(b) uses a cardioid, supercardioid or hypercardioid dynamic microphone mounted located 0.5m vertically above the front skirt. This position would require boosting and equalisation of the mid frequencies since the tenor pan radiates at a significantly lower level in this location for partials in the 400 to 800 Hz range. The microphone should be aimed at the centre of the bowl to maximise the reception of all the frequencies.

![Figure 10](image)

**Figure 10.** A cardioid, supercardioid or hypercardioid dynamic microphone located 0.5m vertically (a) below the front skirt and (b) above the front skirt

7. Conclusions

This paper has extended on the work done in Copeland (2002) on microphone placement for steelpan recording and live performances. Several options are presented based on the radiation patterns generated for a tenor steelpan, with the most significant being that at least two microphones are required for optimum recording of the instrument, preferably with one placed above and one below the instrument. It is also noteworthy that Copeland's (2002) results and observations for a Clifford Alexis double second steelpan, have also been shown to occur in the Kelman tenor pan tested for this paper, so that these new recommendations may be applicable to other steelpan instruments.

Until alternative techniques, for example those pickups based on strain gauges, piezo-electrics or magnetic proximity, as described in Copeland (1996), are refined or new ones discovered which have all of the advantages of microphones and none of the disadvantages, the information presented in this paper, should result in considerable improvement in the recorded sound obtained from the Caribbean steelpan.

References:


Shure (2009), *Microphone Techniques for Recording*, Shure Educational Publication, Shure Incorporated, USA, p.20

Authors’ Biographical Notes:

Fasil Muddeen is a Lecturer in the Department of Electrical and Computer Engineering at The University of the West Indies (UWI, St Augustine Campus, Trinidad and Tobago. His areas of research include the acoustics of the steelpan, digital signal processing, electronics and instrumentation. Dr. Muddeen is a registered engineer with the Board of Engineering of Trinidad and Tobago and is the current Chairman of the IEEE Trinidad and Tobago Section.

Brian Copeland is the current Dean of the Faculty of Engineering and a Professor in Electrical and Computer Engineering at The University of the West Indies. He is the Coordinator, Steelpan Initiatives Project and Convener of the Steelpan Research Centre, UWI. Some of his many research interests include Steelpan technology: amplification, digital synthesis, sound field mapping and modal studies; Technology Management in developing countries; Design of numerically stable advanced control system algorithms with special emphasis on H-2 (H2)- and H-Infinity (H\(\infty\)) - norm optimisation for strictly proper systems; and Supervisory Control and Data Acquisition Systems (SCADA) and Distributed Control Systems (DCSs) for wide area computer monitoring and control. Professor Copeland was the first recipient of the Order of the Republic of Trinidad and Tobago and a joint recipient of the Chaconia Medal Gold as a member of the G-Pan team.
In Search of the Knowledge Management Practices in Organisations: A Review

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Abstract: There has been extensive research on knowledge and knowledge management (KM) in the past two decades. KM has progressed from an emergent concept to an increasingly common function in industrial enterprises. As evidence of its maturity as an area of academic study, an increasing number of journals devoted to KM have been created. This paper presents a review of the literature addressing the KM concepts, approaches and frameworks, and the factors affecting the KM practices in organisations. The review covers the publicly available KM literature through library catalogue and electronic search over a period from 1997 to 2010. The distribution of KM literature and articles in regard to the scope of the research is presented. It explores the multi-disciplinary nature of KM and discusses the components of the KM process in organisational settings. Several dominant KM approaches, and selected frameworks and models in industrial application domains are also discussed along with the need for future research on investigating the KM competence at both firm’s and industry’s levels.

Keywords: Knowledge management, approaches, frameworks, factors, performance

1. Introduction

The foundation of organisational competitiveness in the contemporary economy has shifted from tangible resources to knowledge. Organisations are beginning to recognise the need to tap into knowledge assets diffused around the organisation in order to remain agile (Khatibian, Hasan ghooli pour, and Jafari 2010). Knowledge has now become a kind of strategic resource in enterprises, and therefore, the management of this strategic resource shows its explicit importance (Ho 2009). The ability to create knowledge and interact it with people in organisations has been recognised as a strategic capability (Armistead 1999). Wei, Choy, and Yew (2009) also regard knowledge as the nucleus of global economic transformation and competitive advantage of an organisation.

Knowledge management (KM) is a relatively new and evolving discipline that has garnered interest from both academicians and practitioners (Migdadi 2009; Ma and Yu 2010). This is a strategic management concept drawing from various disciplinary areas (Pillania 2009) and has emerged as a phenomenon with wide-ranging implications for organisational performance and competitiveness (Carneiro 2000; Chourides, Longbottom, and Murphy 2003). There has been an abundance of published research related to KM since the 1990s (Yiu 2006; Serenko and Bontis 2009; Heisig 2009; Ma and Yu 2010). Besides, initiatives carried out by standardisation bodies in Australia (Standards Australia 2001, 2003, 2005), Britain (BSI 2001, 2003a, 2003b, 2005a, 2005b) and Germany (DIN 2006), as well as on the European Level (CEN 2004) have tried to achieve a common understanding about KM.

KM has been gaining momentum as the means toward organisational survival and growth. As investments in various KM initiatives inflate, the call for coherent and comprehensible principles and practices to guide KM implementation efforts has increased (Khatibian, Hasan ghooli pour, and Jafari 2010). KM implementation remains an enigma and a source of frustration in many organisations irrespective of their size, business nature and locations (Wang and Ahmed 2005). There has been a growing concern about the KM adoption and its impact on performance measurements in organisations (Zack, McKeen, and Satyendra 2009; Pun and Nathai-Balkissoon 2011). This paper explores the KM concepts and practices by examining the recent studies conducted in different countries and published in journals from 1997 to 2010. A review of these articles was made to investigate the state of contemporary KM concepts, various models and frameworks of KM practices, as well as the trends in KM studies.
2. A Review of KM Literature

2.1 Method of literature search

KM research has significantly grown since its inception in the 1990s. However, Maqsood, Walker, and Finegan (2007) argue that researchers and the academic community struggle to explicate a realistic KM philosophy that can be readily put into practice and successfully implemented. KM is an evolving discipline that had become increasingly popular, judging from the large number of papers submitted in the past decade (Yiu 2006; Pun and Nathai-Balkissoon 2011). Despite the wide reach of the discipline, difficulty persists in implementing KM practices within organisations.

Gordon and Grant (2005) performed an analysis of KM literature from 1986 to 2004, and found that the publications were minimal prior to 1996, but began increasing steadily thereafter. Pun and Nathai-Balkissoon (2011) conducted a similar literature search on KM and organisational learning (OL) largely through the use of multiple ProQuest databases spanning the period from 1996 to 2009 and found that there were an uneven dispersion and diverse range of KM/OL applications. The wide-ranging fields indicate that many researchers and practitioners are aware of the theories of KM and OL and have been integrating them into organisational practices.

In order to identify the determinants of KM practices and performance in organisations, an initiative was made to search academic peer-reviewed journal articles in KM and related areas over a period of 1997 to March 2006 initially (Yiu 2006) and then extending to 2010. For the purpose of data acquisition, the scientific publications relevant to KM were investigated. A similar method as advocated by Gordon and Grant (2005) and Pun and Nathai-Balkissoon (2011) was adopted. Online databases, mainly ProQuest (2010) and Emerald Insight (2010), were hired and the search tactics are described as follows:

- The term ‘knowledge management’ was searched in citations and abstracts;
- A review of the categorised list of results was then performed, and the search was narrowed to results in the sub-category ‘Knowledge’, ‘Performance’, ‘Frameworks’, ‘Models’, ‘Tools’ and ‘Factors’;
- Each paper listed from the ProQuest database search was evaluated for relevance to the objectives of the study i.e. to identify the determinants of KM practices and performance in industries;
- Further searches were performed within the Emerald Insight database to locate academic and scientific journal articles. KM conference documentations and various internet sources were also accessed.

The searches yielded over a thousand articles. With respect to the objectives of the study, each of the articles was examined to ensure that the content was relevant. Many articles had a holistic and/or pragmatic approach to KM while others focused few specific aspects of KM such as processes, policy, performance issues, tools and techniques were also included if they were written in the KM context (Yiu 2006; Yiu, Sankat, and Lewis 2007).

Eventually, a total of 588 articles were selected from 82 journals under six categories, namely: Case studies, Conceptual paper, General/ literature review, Research paper, Technical paper, and Viewpoint. In addition, the examination of literature also incorporated materials that were abstracted from other published sources including KM texts, conference proceedings and technical reports.

2.2 Examination of articles by year and categories

All searched journal articles were grouped by their nature according to the classification of articles advocated by Emerald Insight (2010). Table 1 depicts a summary of the article searches by year and categories. It is shown that out of 588 articles, about 55.8 per cent (i.e. 328 articles) were research papers in the KM domains. The second and third largest groups of articles were 84 conceptual papers (i.e. 14.3 per cent) and 71 general/literature review type of papers (i.e. 12.1 per cent), respectively. Record shows that only 9.7 per cent (i.e. 57 articles) were case studies. Both viewpoint (i.e. 28 articles) and technical papers (i.e. 20 articles) together accounted for only 8.1 per cent of article searches over the studied period (i.e. from 1997 to 2010). While examining the 588 journal articles published by year, there has generally been an increasing trend with up-and-down pattern. Throughout the studied period, the trend started from less than 10 articles published in 1997/98 towards the peak of 93 articles in 2008 and 82 articles in 2009. Another 40 publicly available articles in 2010 that fulfilled the search criteria were included.

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Table 2 depicts a list of 82 refereed journals in KM and related areas. It showed that the theme-searched articles published in Journal of Knowledge Management accounted for some 34.9 percent of searched articles (i.e. 205 papers) for the period, followed by VINE (The Journal of Information and Knowledge Management, i.e., 52 papers, 8.8 per cent), The Learning Organisation (i.e., 43 papers, 7.3 per cent) and Industrial Management and Data Systems (i.e., 32 papers, 5.4 per cent). These four journals have included some 56.4 per cent of articles in the searched-theme areas. Other more common journals with the numbers of 10-16 KM articles published were Strategic Direction, Business Process Management Journal, Management Decision, Journal of Manufacturing Technology Management, and Kybernetes.

Besides, a sum of 109 KM articles were published in sixteen journals (i.e. Ref. 10-29 in Table 2) and each of which published 4-9 articles. Another 53 articles were published in 14 journals (i.e. Ref. 30-53) and each of which published 2-3 articles. The rest of 28 articles were published in non-main steam journals (Ref. 54-82). With respect to the diverted nature of 82 journals, it has revealed that KM is multi-disciplinary in nature. With its domains on knowledge identification, acquisition, creation, storage, dissemination, refinement and application, KM cuts across different disciplines and organisational settings from business management, marketing, education management, information and library management, learning organisation, engineering and so on.

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<td>1.5</td>
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<tr>
<td>11.</td>
<td>Journal of Management Development</td>
<td>8</td>
<td>1.4</td>
</tr>
<tr>
<td>12.</td>
<td>International Journal of Manpower</td>
<td>7</td>
<td>1.2</td>
</tr>
<tr>
<td>13.</td>
<td>5 Journals and each with six articles (including: Aslib Proceedings; Journal of Workplace Learning; International Journal of Productivity and Performance Management; Library Management and Measuring Business Excellence)</td>
<td>30</td>
<td>5.1</td>
</tr>
<tr>
<td>14.</td>
<td>7 Journals and each with five articles (including: Development and Learning in Organisations; Engineering, Construction and Architectural Management; European Business Review; Information Management &amp; Computer Security; Information Technology and People; Journal of Enterprise Information Management and Management Research News)</td>
<td>35</td>
<td>6.0</td>
</tr>
<tr>
<td>25-29.</td>
<td>5 Journals and each with four articles (including: Benchmarking: An International Journal; Handbook of Business Strategy; Human Resource Management International Digest; International Journal of Quality and Reliability Management; and Journal of European Industrial Training)</td>
<td>20</td>
<td>3.4</td>
</tr>
<tr>
<td>30-36.</td>
<td>7 Journals and each with three articles (including: Business Strategy Series; European Journal of Marketing; Journal of Technology Management in China; Leadership &amp; Organisational Development Journal; Library Review; International Journal of Educational Management; and Managerial Auditing)</td>
<td>21</td>
<td>3.6</td>
</tr>
</tbody>
</table>

| Total: | 588 | 100 |

* Remarks: Data updated to June 2010.
KM is thus a strategic management concept because knowledge is recognised as a key strategic resource and also because, like strategic management, it is a unifying concept drawing from various disciplinary areas like information systems, human resource management, economics, operations management (Yiu 2006; Pillania 2009). The wide-ranging fields indicate that many researchers and practitioners are aware of the theories of KM and have been integrating them into organisational practices. Nevertheless, most of the literature on KM and its application has, until recently, been centered on large organisations. Pertinent issues in small businesses have to a large extent been neglected. However, Wong and Aspinwall (2005) argue that small businesses do not necessarily share the same characteristics and ideals as large ones. There are certain unique features of small businesses that need to be understood before KM is implemented in their environment.

The literature search findings show that a majority of selected articles categorised as ‘research’ type fell into empirical studies. Other articles were conceptual or theoretical in nature, and were geared towards the development of theories related to KM practices. The ensuing sections present the findings from the review, and discuss their implications on the KM adoption and performance measurements in organisations. These include: 1) the notion of knowledge, 2) the concepts of KM, 3) historical developments of KM, 4) the KM process and components, 5) the approaches of KM adoption and implementation, and 6) some KM frameworks in applications.

3. Notion of Knowledge

The term ‘knowledge’ signifies an area of conflict for many years. Diakoulakis et al (2004) contend that this is attributable to the existence of resemblance concepts, such as data and information, which can easily approximate some forms of knowledge. Knowledge as defined by the Oxford Dictionary is familiarity gained by experience. It is product of human reflection and experience, while data is raw observations of the past, the present or the future and information is the pattern(s) that individuals instil on data (Davenport 1997). It is generally accepted that there is a hierarchical relationship between data, information, knowledge, and wisdom, with data seen as a primary or raw form, information being a processed form that gives usefulness to data, and knowledge being the result of judicious application of information (Bajaria 2000; Rowley 2006).

Polyani (1958) firstly defined tacit and explicit categorisations of knowledge. According to Roth (2003), knowledge has two dimensions; firstly, it exists on the individual, group and organisational levels of a firm; and secondly, it is either explicit or tacit. Explicit knowledge is observable and can be embedded in tools, processes and rules. This type of knowledge is more tangible and can be found in written documents. For instance, some of the knowledge involved in the use and improvement of technologies can be written down in detail in procedures manuals and use instructions (Gupta, Iyer, and Aronson 2000). On the other hand, tacit knowledge is difficult or impossible to be articulated in written documents (Herschel, Nemati, and Steiger 2001), and is tacitly transmitted and learned (Carneiro 2000). Tacit knowledge resides innately in people and tends to be embedded by way of their experiences, values, intuition, values, and contextual information (Davenport and Prusak 1998; Gupta, Iyer, and Aronson 2000). This type of knowledge is highly subjective and difficult to capture or convey in a straightforward manner.

In its most basic form, knowledge can be thought of as information that is “contextual, relevant and actionable” (Bose 2004). Knowledge allows the making of predictions, casual associations, or descriptive decisions about what to do (del-Rey-Chamorro et al 2003). Beyond the ascertainment of the proper terminology about knowledge, Nonaka and Takeuchi (1995) contend that a thorough analysis of all possible types of conversion between tacit and explicit knowledge is useful as this fact plays a critical role in the efficient and effective management of knowledge at an organisational level. There are conflicting opinions about the role and value of knowledge in organisations, with some supporting the view that knowledge is an ‘object’ for capture and transfer, and others proposing that knowledge must be managed as a process as it is impacted by people and systems within the organisations (Hara and Schwen 2006).

Knowledge is complex, multidimensional and gleaned and imparted in different ways to different people (Bose 2004). In organisations, knowledge often becomes embedded not only in documents or repositories but also in organisational routines, processes, practices, and norms. In other words, corporate culture, best practices, core competencies, skills, or strategic visions are critical parts of the total stocks of knowledge in an organisation (Bose 2004; Diakoulakis et al 2004). It becomes essential to continue developing and managing company’s knowledge in order to keep abreast of continuing change from the internal and external environment (Davenport and Prusak 1998) and to gain advantages (Lee 2000).

4. KM and Its Historical Developments

4.1 The KM Concepts

According to Malhotra (2005), KM embodies organisational processes that seek synergistic combination of data and information-processing capacity of information technologies, and the creative and innovative capacity of human beings. KM continues to evolve as a discipline, yet even basic features that define a discipline have to be established (Cavaleri 2004, 2008).

Earl (1999) argues that no universally accepted definition of KM exists despite there is a great deal of interest in it. Some selected connotations of KM in the literature are given in Table 3. The examination of existing definitions of KM shows a wide spectrum of viewpoints ranging from more mechanistic one to more socially orientated.

Table 3. Selected connotations of KM

<table>
<thead>
<tr>
<th>Authors</th>
<th>Connotations of KM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wigg (1993)</td>
<td>KM deals with the process of creating value from an organisation’s intangible assets.</td>
</tr>
<tr>
<td>APQC (1996)</td>
<td>KM is getting the right information to the right people at the right time, helping people create knowledge and sharing and acting on information.</td>
</tr>
<tr>
<td>Quintas, Lefrere, and Jones</td>
<td>KM is to discover, develop, utilise, deliver and absorb knowledge inside and outside the organisation through an appropriate management process to meet current and future needs.</td>
</tr>
<tr>
<td>(1997)</td>
<td></td>
</tr>
<tr>
<td>Davenport, De Long, and</td>
<td>KM is managing the corporation’s knowledge through a systematically and organisationally specified process for acquiring, organising, sustaining, applying, sharing and renewing both the tacit and explicit knowledge of employees to enhance organisational performance and create value.</td>
</tr>
<tr>
<td>Beers (1998)</td>
<td></td>
</tr>
<tr>
<td>Liebowitz (1999)</td>
<td>KM is an amalgamation of concepts borrowed from the artificial intelligence/knowledge-based systems, software engineering, business process re-engineering (BPR), human resources management, and organisational behaviour.</td>
</tr>
<tr>
<td>Gupta, Iyer, and Aronson</td>
<td>KM is a process that helps organisations find, select, organise, disseminate and transfer important information and expertise necessary for activities.</td>
</tr>
<tr>
<td>(2000)</td>
<td></td>
</tr>
<tr>
<td>Bhatt (2001)</td>
<td>KM is a process of knowledge creation, validation, presentation, and distribution and application.</td>
</tr>
<tr>
<td>Horwitch and Armacost</td>
<td>KM is the creation, extraction, transformation and storage of the correct knowledge and information in order to design better policy, modify action and deliver results.</td>
</tr>
<tr>
<td>(2002)</td>
<td></td>
</tr>
<tr>
<td>Wong and Aspinwall (2004)</td>
<td>KM is the management of knowledge-related processes or activities, based on realistic resources in order to create competence, value and continual success for the organisation.</td>
</tr>
<tr>
<td>Hung et al (2005)</td>
<td>KM is a systemised and integrated managerial strategy, which combines information technology with the organisational process.</td>
</tr>
<tr>
<td>Yiu and Sankat (2007)</td>
<td>KM comprises a range of practices used by organisations to identify, create, represent, and distribute knowledge for reuse, awareness and learning.</td>
</tr>
<tr>
<td>Pillania (2009)</td>
<td>KM is defined as a systematic, organised, explicit and deliberate ongoing process of creating, disseminating, applying, renewing and updating the knowledge for achieving organisational objectives.</td>
</tr>
<tr>
<td>Sbarcea (2010)</td>
<td>KM is an integrated approach of creating, sharing and applying knowledge to enhance organisational productivity, profitability and growth.</td>
</tr>
</tbody>
</table>

Pillania (2009) adds that KM is a comprehensive concept and draws from various disciplines including information systems (IS), information technology (IT) and human resource management (HRM). Malhotra (2005) also argues that KM is concerned with building databases, measuring intellectual capital, building intranets, sharing best practices, leading cultural change, fostering collaboration and creating virtual organisations. Moreover, the concepts of KM are integrally linked with OL (Pemberton and Stonehouse 2000; Bennet and Tomblin 2006), and both play a role in the operation or establishment of a learning organisation (LO) and a chaordic organisation (CO) or chaordic enterprise (CE) (van Eijnatten and Putnik 2004a, 2004b). Review of literature shows that there had been a wider practice of KM/OL integration for the enhancement of organisational performance (Ajmal, Kekale, and Takala 2009; Theriou and Chatzoglou 2009).

McAdam and McCreedy (1999) argue that a rapidly increasing body of knowledge relating to KM covers many different disciplines and areas of interest to academics and practitioners. Nevertheless, there has been a lack of clarity regarding the KM concept for them (Pillania 2009). For instance, data management, information management, IS/IT, HRM, intellectual property (IP) rights management are all associated with the KM concept. However, they are not KM or cannot be termed as KM. In practice, they serve as facilitating systems/practices and/or just the components of KM process (Yiu 2006; Pillania 2008a, 2008b). For example, KM is used to codify as much tacit knowledge as possible and document into explicit form, so that, if the concerned employee leaves the company, some part of his/her knowledge still remains with the company. However, if the KM concept is used in its true spirit, it can lead to sustainable competitive advantage.

Many studies regard KM as a valuable strategic tool for decision-making (Malhotra 2005). KM is an emerging field that has commanded attention and support from much of the industrial community. It is a trans-disciplinary approach to improving organisational outcomes through maximising the use of knowledge (Standards Australia 2005). With KM as the strategic intent, the current management focus is on how to leverage knowledge faster and better than competitors (Thite 2004). As greater numbers of firms in virtually
According to Metaxiotis, Ergazakis, and Psarras (2005), likely become a strategic necessity. For every industry sector engage in KM practices, this will likely become a strategic necessity.

4.2 Historical Developments of KM

According to Metaxiotis, Ergazakis, and Psarras (2005), knowledge management has its origins in a number of related business improvement areas, such as business process re-engineering (BPR), total quality management (TQM), information systems (IS) and human resources management (HRM). Pillania (2009) adds that the KM concept historically emerged from three different continents in different ways. The focus of KM in Europe was on measuring intangibles and intangible accounting. The focus in Japan was on creating new knowledge. The focus in the United States (US) was on exploiting existing knowledge and information using information systems. As time passed, the US model became more prominent. For instance, many authors (e.g. Lin and Lee 2005; Shah, Eardley, and Wood-Harper 2007) regard KM as primarily technology-centred and driven.

Moreover, Metaxiotis, Ergazakis, and Psarras (2005) contend that three KM generations could chronologically be identified. During the period of 1990-1995, many initiatives focused on defining KM, investigating the potential benefits of KM for businesses, and designing specific KM projects (Nonaka and Takeuchi 1995; Wiig 2007). First-generation KM was characterised by the development of electronic databases that stored bits of knowledge inputted by employees (Sasson and Douglas 2006). Much research has been focused on the utilisation of digital and electronic technology to capture critical knowledge and integrate KM capabilities in organisations (Lytras and Pouloudi 2003). Besides, progress was on artificial intelligence research in the direction of knowledge representation and storing (Metaxiotis, Ergazakis, and Psarras 2005).

As reflected in literature, KM has moved from being technology dependent in the mid 1990s to a greater emphasis on socialisation in the late 1990s and early 2000s (Sasson and Douglas 2006). The second generation started from the mid 1990s with many corporations setting up new jobs for KM specialists. The different sources of KM became combined and also quickly absorbed to everyday organisational discourse. During this generation, KM research touched upon knowledge-definitional issues, business philosophies, systems, frameworks, operations and practices, and advanced technologies (Metaxiotis et al 2003). Besides, this generation emphasised systemic organisational change where management practices, measurement systems, tools and content management needed to be co-developed.

The third generation of KM emerged around the mid-2000s with new insights, practices, methods and results (Paraponaris 2003; Metaxiotis, Ergazakis, and Psarras 2005). The third generation fostered the link between knowing and action with greater integration into the enterprise’s philosophy, strategy, goals, practices, systems and procedures.

4.3 The KM Process and Its Components

Recent literature shows that firms use a variety of means and approaches to combine, sort, and process the environmental data to produce timely and relevant information for forming, monitoring, evaluating, and modifying organisational strategy (Carneino 2000; Khatibian, Hassan gholoi pour, and Jafari 2010). In such context, Wong and Aspinwall (2005) contend that KM is an emerging set of organisational design and operational principles, processes, organisational structures, applications and technologies. In particular, knowledge-related processes or activities (or in short, the KM process) are about knowledge creation, validation, presentation, distribution and application activities (Bose 2004; Wong and Aspinwall 2004). Diakoulakis et al (2004) argue that the focus of KM is on the integration and coordination of individuals' knowledge, that is, the appropriate “application/management” of current organisational knowledge, and the “creation” of knowledge. Pillania (2009) adds that KM basically involves three things – knowledge creation, knowledge dissemination and knowledge implementation.

The KM processes are divisible into a number of inter-connected activities that depend on the particular industry, the nature of the firm and the strategy it adopts (Ahmed, Lim, and Zairi 1999; Wang 2002; Wang and Ahmed 2005). Table 4 depicts the eight components of the knowledge value-adding process.

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<table>
<thead>
<tr>
<th>KM Processes</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Knowledge Identification</td>
<td>Searching for, and locating new information, ideas and knowledge that are relevant to the organisation.</td>
</tr>
<tr>
<td>2. Knowledge Acquisition</td>
<td>Acquiring knowledge identified to be relevant, and absorbing such knowledge in the specific organisational context.</td>
</tr>
<tr>
<td>3. Knowledge Codification</td>
<td>Codifying tacit knowledge, categorising knowledge acquired and labelling knowledge.</td>
</tr>
<tr>
<td>4. Knowledge Storage</td>
<td>Recording knowledge, retaining and maintaining knowledge, and clearly signposting the knowledge directory.</td>
</tr>
<tr>
<td>5. Knowledge Dissemination</td>
<td>Retrieving knowledge stored, making it available to knowledge seekers and users.</td>
</tr>
<tr>
<td>6. Knowledge Refinement</td>
<td>Improving, transferring and adapting existing knowledge to changed situations, or using existing knowledge in a new way.</td>
</tr>
<tr>
<td>7. Knowledge Application</td>
<td>Putting knowledge into action, utilising knowledge to produce organisational outcomes.</td>
</tr>
<tr>
<td>8. Knowledge Creation</td>
<td>Nurturing, seeding and incubating new ideas, and generating new knowledge that leads to major breakthroughs.</td>
</tr>
</tbody>
</table>

Source: Taken from Wang and Ahmed (2005)
According to Diakoulakis et al. (2004), KM is considered to encompass the processes of “retention-systematisation of knowledge”, “sharing-access of knowledge”, “combination-creation of knowledge”, “exploration of the external environment”, “scanning of the internal context” and the “use of knowledge”. The constituent elements are assumed to possess various cause-effect relationships between them, which are all positive but their strength differs significantly. Moreover, the strengths of these relationships vary when examining organisations with divergent characteristics. The causal nature supposed to exist among the KM processes, as presented in Figure 1, has an operational and basically strategic impact on organisations.

![Figure 1. The causal link of the KM process](image)

Source: Taken from Diakoulakis et al (2004)

KM processes depict the primary activities of the KM value adding chain and are inter-linked. In order to ensure effective KM processes, Bose (2004) argues that organisations must dedicate effort to building infrastructures that enhance knowledge systems, knowledge culture, organisational memory, knowledge sharing, and knowledge benchmarking. Diakoulakis et al (2004) add that KM processes and their enabling capabilities do not automatically lead to performance outcomes. Good inter-linkage and alignment of KM processes would underlie the building of enhanced capabilities, and facilitate the delivery of expected performance outcomes (Diakoulakis et al 2004; Wang and Ahmed 2005).

### 4.4 Factors Affecting KM Practices

Factors underpinning the success of KM can be identified by authors who have researched and written directly on this subject. For instance, Liebowitz (1999) proposed six key ingredients for making KM successful, and suggested the need for a KM strategy with support from senior management, a chief knowledge officer (CKO) or equivalent, a KM infrastructure, knowledge ontologies and repositories, KM systems and tools, incentives to encourage knowledge sharing and a supportive culture.

Lee and Choi (2003) identified seven factors, including collaboration, trust, learning, centralisation, formalisation, skills and IT support that interconnected KM practices. Jennex and Olftman (2004) argued in their study that typical success factors included leadership, investing in people, and developing supporting organisational conditions like technical infrastructure and secured knowledge structure. Besides, Yu, Kim, and Kim (2004) studied a group of 66 Korean firms and found that learning orientation, knowledge-sharing intention, KM system quality, reward, and KM team activity were significantly related to the organisational KM performance. Similarly, Koh, Ryan, and Prybutok (2005) also identified three critical factors, namely 1) strategic alignment and focus; 2) system and data integration; and 3) security and privacy policies.

Another research study conducted by Hariharan (2005) acknowledged that KM would help share knowledge and eliminate reinvention, and proposed seven enablers of KM. These are: 1) strategic focus; 2) alignment with objectives; 3) KM organisation and roles; 4) standard KM processes; 5) culture and people engagement; 6) content under scrutiny; and 7) technology enablement. Moreover, Chong et al (2006) have identified five preliminary success factors for KM implementation and tested them among the Malaysian telecommunication industry. They are business strategy, organisational structure, KM team, K-Map and K-Audit. According to a recent study conducted by Anantatmula and Kanungo (2010), the results show that top management involvement, KM leadership, and the culture of the organisation are the main driving factors based on which one can build a successful KM effort.

The effective implementation of KM is governed and facilitated by certain factors. Organisations can certainly benefit from a more thorough understanding of the factors that are critical to the success of KM. In this context, four categories of KM success factors (namely Environmental/ Market, Company/Operational, People and Technical) are identified (Yiu 2006; Yiu, Sankat, and Lewis 2007). Table 5 contrasts the KM success factors versus related problematic areas under these categories.

### 5. Frameworks of KM Adoption and Implementation

Reviewing the literature, studies on KM practices have been plentiful, but have varied widely in their location, focus, application and depth (Yiu 2006; Heisig 2009; Pun and Nathai-Balkissoon 2011). Reason and Bradbury (2001) argue that organisations need to assess their KM competence and examine how to integrate both technical and human aspects of knowledge acquisition, development and applications. The implementation of KM requires 1) an organisational strategy, 2) processes to carry out the strategy, and 3) measurements to evaluate how well those processes are working (Bose 2004; Yiu and Sankat 2007).
Change through successful KM implementation requires a review of the traditional dictum that implementation follows formulation. Having regards the interdisciplinary nature of KM implementation, Dufour and Steane (2007) contend that the multiple processes (i.e., rational, structural, behavioural, and political) are operating concurrently, and the emerging of new theoretical models and practical approaches would invite a fundamental reassessment of KM implementation and the formulation of KM strategy. Maqsood, Walker, and Finegan (2007) conclude that culture, leadership, and vision issues are becoming more important to KM philosophical underpinnings.

According to Weber et al (2002), a framework is defined as a holistic and concise description of the major elements, concepts and principles of a domain. It aims to explain a domain and define a standardised schema of its core content as a reference for future design implementations. A KM framework explains the world of KM by naming the major KM elements, their relationships and the principles of how these elements interact. It provides the reference for decisions about the implementation and application of KM.

McAdam and McCreedy (1999) conducted a critical review of KM frameworks/models, and classified them into three main categories, namely intellectual capital models, knowledge category models, and socially constructed models for the KM process (Demarest 1997). Malhotra (2005) contends that there are two main categories of KM frameworks, namely ‘technology-push’ versus ‘strategy-pull’ models. The focus of the technology-push model is on mechanistic information processing that relies upon a single-loop response to received stimulus, while the strategy-pull model has built in double-loop process that facilitates organic sense making in organisations (Malhotra 2001, 2005).

Heisig (2009) conducted a quantitative and qualitative analysis of 160 KM frameworks from different origins worldwide. These frameworks are published in the scientific literature, presented at specialised conferences or used in knowledge management initiatives by companies from 1998 to 2003. The result shows that despite the wide range of terms used in the KM frameworks an underlying consensus was detected regarding the basic categories used to describe the KM activities and the critical success factors of KM. Moreover, Pun and Nathai-Balkissoon (2011) reviewed 18 studies reported in publicly available journals from 1996 to 2009 and studied 14 KM/OL frameworks and models, focusing on recognition of major approaches and contributions of KM and OL practices in industry. Systems approaches,
culture, and the LO and CO/CE concepts are among the most popularly cited factors for the development of KM/OL frameworks.

In search of the KM competencies in practices, this paper attempted to review ten (10) selected KM frameworks and models from literature. Table 6 presents a comparison among them with respect to their strengths (or success factors) and weaknesses (or obstacles) in applications. These frameworks and models are:

1) Lee (2000)’s Knowledge Sharing Framework – This framework identifies 5 stages of knowledge requirements experienced by workers depending on their respective stage or ‘lifecycle’ within a company. It caters to various employee knowledge needs, determines the maturity of a company’s knowledge sharing system, and identifies areas for improvement of that system. However, the framework does not provide a guide or any stepwise approach for company to measure/monitor the improvement in KM practice.

<table>
<thead>
<tr>
<th>Author, Year</th>
<th>Model/Framework</th>
<th>Strengths or Success Factors</th>
<th>Weaknesses or Obstacles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lee (2000)</td>
<td>Knowledge Sharing Framework</td>
<td>· The framework illustrates various employee knowledge needs, determines the maturity of a company’s knowledge sharing system, and identifies areas for improvement of that system.</td>
<td>· The framework does not guide a company as to how improvement can be brought about; no stepwise approach proposed.</td>
</tr>
<tr>
<td>Szulanski (2000)</td>
<td>Model for Knowledge Transfer</td>
<td>· The collection of empirical data from 122 knowledge transfer processes within 8 firms, and data collected was applied within the model.</td>
<td>· The knowledge transfer processes and factors are subject to further verification of empirical evidence.</td>
</tr>
<tr>
<td>Argote, McEvily, and Reagans (2003)</td>
<td>Integrative KM Framework</td>
<td>· The framework stresses the importance of building the integrative relationships between the KM outcomes and context.</td>
<td>Variations could exist in the interpretation of contents for the framework, and no clear definition of terms to facilitate the analyses.</td>
</tr>
<tr>
<td>Siemieniuch and Sinclair (2004)</td>
<td>Process Framework for Knowledge Management</td>
<td>· This is an independently developed framework parallel to the sub-processes of Social Learning Cycle. It promotes acceptability of the framework.</td>
<td>· The process framework is rather complex and may be intimidating to first-time users. More financial demands and guidance are needed from KM experts and consultants.</td>
</tr>
<tr>
<td>Dikoulaklis et al (2004)</td>
<td>Holistic Knowledge Management Model</td>
<td>· The model raises an innovative approach in strategic thinking, shifting the interest from the processes, the measures and the objectives in isolation to an integrated network of cause-effect relationships, so as to investigate core competencies and develop competitive advantages.</td>
<td>The cause-effect relationships have to be quantified. The inference process is not a straightforward task, and the related costs of the applied actions/strategies cannot be easily estimated. Some “environmental” factors may be unavoidably excluded.</td>
</tr>
<tr>
<td>Zuber-Skerritt (2005)</td>
<td>Personal Knowledge Management Model</td>
<td>· This Action research approach recognises personal learning that impacts organisational KM, and promotes application of a systematic approach to knowledge capture, documentation, and sharing.</td>
<td>· The emphasis of action learning approaches looks intensively at situations, practices, and outcomes. The application of this approach would limit work to one or a very few cases at a time.</td>
</tr>
<tr>
<td>de Barros Campos (2008)</td>
<td>Knowledge Life Cycle Model</td>
<td>· The double-loop process begins with a problem leading to a solution attempt, which is then tested, evaluated, and possibly refuted so as to eliminate errors. New knowledge is generated for the purpose of adjustment to actions. New problems motivate other cycles and the continuous re-evaluation of knowledge.</td>
<td>· The process does not present problems. The same does not occur in double-loop learning, when error correction calls for adjustment of norms, strategies, and presuppositions.</td>
</tr>
<tr>
<td>Jalalinia, and Nekui Yazdi (2009)</td>
<td>KM-Business Process Outsourcing Framework</td>
<td>· The framework focuses on BPO and its lifecycle and risks. It helps reduce the risks and pitfalls of BPO as evidenced in the case company.</td>
<td>· There is a lack of empirical evidence to validate the pragmatism and applicability of the framework.</td>
</tr>
<tr>
<td>Kang and Kim (2010)</td>
<td>Integrative Framework on KM and NPD</td>
<td>· The framework explains the interaction between tacit and explicit knowledge and how knowledge is created, and allows business practitioners to better understand complex cross-functional activities and to focus their resources for NPD.</td>
<td>· The applicability of the framework needs further verification of empirical evidence.</td>
</tr>
<tr>
<td>Massingham (2010)</td>
<td>Knowledge Risk Management Framework</td>
<td>· The framework has 3 steps. Step 1 calculates the level of risk associated with each of the organisation’s main activities. Step 2 calculates the level of risk associated with the knowledge necessary to manage the risk factors for each activity. Step 3 prioritises risks for action.</td>
<td>· This is a conceptual framework. Its application needs further verification of empirical evidence.</td>
</tr>
</tbody>
</table>
2) Szulanski (2000)’s Model for Knowledge Transfer – This identifies various stages of knowledge transfer and factors affecting ease of transfer at each stage. This is a structured model comprised of a comprehensive list of 122 identifiable processes of knowledge transfer in different stages. However, these knowledge transfer processes and factors are subject to verification of empirical evidence.

3) Argote, McEvily, and Reagans (2003)’s Integrative KM Framework – There are two dimensions advocated in the framework. The first dimension deals with the KM outcomes (namely, knowledge creation, retention, and transfer), while the second deals with the KM context (i.e., individuals, groups or organisations). The framework stresses the importance of building the relationships between the KM outcomes and context. However, variations could exist in the interpretation of integrative contents for the framework, and no clear definition of terms to facilitate the analyses.

4) Siemieniuch and Sinclair (2004)’s Process Framework for Knowledge Management – This is a four-stage framework that assists companies in managing knowledge across multiple projects. Three categories of knowledge are considered within projects (i.e., intra-project), between projects (i.e., inter-project), and across sectors (i.e., cross-sectorial). It defines KM problems empirically and helps organisations to address them. This is an independently developed framework parallel to the sub-processes of Social Learning Cycle. However, more guidance from KM experts and consultants is needed that helps users to work along with the four-stage methodology.

5) Diakoulakis et al (2004)’s Holistic Knowledge Management Model – This identifies the use of systems thinking logic to examine structures underlying complex phenomena and consolidate the various KM approaches. The model draws its strengths on the development of an integrated network of cause-effect relationships that could help determine core competencies and develop competitive advantages. However, the inference process is not a straightforward task. Some “environmental” factors may be unavoidably excluded in quantifying the relationships during the process.

6) Zuber-Skerritt (2005)’s Personal Knowledge Management Model – This is an action learning and action research model which links values and action approaches, and promotes personal-level learning. The model recognises seven (7) types of personal knowledge through reflection, collaboration, feedback and teamwork, visioning, openness to self-criticism, learning from others, and recognition and celebration. The strengths of the model are to recognise personal learning that impacts organisational KM, and encourages action learning whereby people interact, share, and learn from one another’s actions and experiences, and reflect on what is learned. However, its weakness lies significantly on the constraints of action learning that would limit work to one or a very few cases at a time.

7) de Barros Campos (2008)’s Knowledge Life Cycle Model – This model envisages a double-loop Decision Execution Cycle (DEC) that is composed of planning, acting, monitoring, and evaluation stages. The double-loop process begins with a problem leading to a solution attempt, which is then tested, evaluated, and possibly refuted to eliminate errors. Adopting this model could generate new knowledge for the purpose of adjustment to actions. New problems motivate other cycles and the continuous re-evaluation of knowledge. However, the process itself does not identify or present problems. The same does not occur in double-loop learning, when error correction calls for adjustment of norms, strategies, and presuppositions.

8) Mahmoodzadeh, Jalalinia, and Nekui Yazdi (2009)’s KM-Business Process Outsourcing (BPO) Framework – This provides a pragmatic BPO methodology with KM for performing each step of BPO lifecycle and reducing associated risks and pitfalls. The framework focuses on BPO and its lifecycle and associated risks, and helps reduce them as evidenced in the case company. However, there is a lack of empirical evidence to validate the applicability of the framework.

9) Kang and Kim (2010)’s Integrative Framework on KM and NPD – This explains the interaction between tacit and explicit knowledge and how knowledge is created, and allows business practitioners to better understand complex cross-functional activities and to focus their resources for new product development (NPD). The major strength of the framework is of its integrative nature without losing distinctive features of KM and NPD. However, its applicability is subject to verification of empirical evidence.

10) Massingham (2010)’s Knowledge Risk Management Framework – This framework intersects risk management (RM) with KM, and addresses the problem of environmental complexity by using KM tools and techniques to reduce uncertainty and make the risk “learnable”. It has 3 distinct steps. Step 1 calculates the level of risk associated with each of the organisation’s main activities. Step 2 calculates the level of risk associated with the knowledge necessary to manage the risk factors for each activity, and Step 3 prioritises risks for action. However, this conceptual framework lacks of evidences on its pragmatism in industry applications.

It was found that conceptual knowledge transfer, knowledge acquisition and creation, and learning models underlie much of the work being done in the field. Despite being holistic in nature, most of these KM frameworks and models tend to emphasise different aspects of KM. Some frameworks focus on the knowledge cycle (e.g., Siemieniuch and Sinclair 2004; de Barros Campos 2008), and integrate with other management disciplines/processes, such as BPO (Mahmoodzadeh, Jalalinia, and Nekui Yazdi 2009), NPD (Kang and Kim 2010), and RM (Massingham 2010). Several KM frameworks were sought to capture the way that knowledge processes worked in very narrow fields
such as knowledge acquisition and knowledge supply (e.g. Lee 2000) or specific knowledge process (e.g. Szulanski 2000). The majority of KM frameworks do not address in an equal way on technical aspects (such as technology and organisational structures) versus non-technical aspects (such as culture and human resources management).

Moreover, conceptual knowledge transfer (Lee 2000) and learning models (Argote, McEvily, and Reagans 2003; Diakoulakis et al 2004; Siemieniuch and Sinclair 2004; Zuber-Skerritt 2005) underline considerable amount of the recent work in KM, regardless of the specifics of practice, sector, or country. Many authors (e.g., Diakoulakis et al 2004; de Barros Campos 2008; Massingham 2010) also indicate the need for further research on several fronts, to conceptually propose and/or empirically investigate how KM could be encouraged or maximised. The identification of the strengths and weaknesses/obstacles of these models/frameworks could help derive a host of determinants (or enablers) for KM practices.

7. Discussions and Conclusion

Nowadays, many industry leaders are engaging in KM in order to leverage knowledge both within their organisation, and externally, to their shareholders and customers. The embedding and embracing of KM within an organisation requires attention to objectives, types of knowledge, technologies, and organisational roles.

Okes (2005) advocates that questions to be addressed in KM include: 1) what knowledge is critical to the organisation? 2) Where and how does the organisation gain that knowledge? 3) What does the organisation do with it? 4) How is it used, distributed and stored? 5) To whom does the organisation go for help, and who comes to the organisation for help? and 6) what metrics are used to track the management of knowledge? The challenges for today’s organisations are to 1) match and align performance measures with business strategy, structures and corporate culture, 2) deploy the measures so that the results are used and acted upon, and 3) integrate KM with performance measurement (PM) to attain sustainable competitive performance (del-Rey-Chamorro et al 2003; Pun and White 2005). Without measurable success, enthusiasm and support for KM is unlikely to continue. Bose (2004) contends that the best and most logical approach to measuring the impact of KM on an organisation’s performance is to tie-in measurement of KM with the organisation’s overall PM systems. However, it has not been unusual to find many of these systems sending confusing and occasionally contradictory signals to organisations (Kennerley and Neely 2002).

There had been an increasing trend of publications with less than ten (10) articles in 1997/98 towards 93 and 82 articles in 2008 and 2009, respectively. Of 588 searched articles in 82 journals, research papers have been dominating the scene, followed by conceptual papers and general/literature reviews. The diverted nature of journals has revealed that KM is multi-disciplinary in nature and cuts across different disciplines and organisational settings. Core themes of KM process relate to: 1) the creation of knowledge repositories; 2) the improvement of knowledge acquisition; 3) the enhancement of the knowledge environment; and 4) the management of knowledge as an asset. This paper also reports the review of common approaches and frameworks/models that govern KM adoption and implementation in organisations. Some studies have forwarded the call for systems integration and organisational effectiveness. The findings provide an understanding of implementation from a holistic perspective, which allows divergent paradigms and perspectives to co-exist.

This paper sheds an effort on reviewing KM literature that leads to a clarification of the ways in which the field of KM can yield synergistic results in organisations, and an appreciation of further avenues for studies that can benefit the field of KM. Reviews show that the impact of KM on an organisation’s performance is strongly tied to the ability of an organisation to identify where KM will be of most value. The future usage of KM is heavily dependent on both the quality of the metrics and whether output generated by these metrics management would provide tangible value addition to the organisations. This necessitates research efforts to investigate the determinants of KM practices, examine the effectiveness of various measures on organisational performance, and devise an integrated paradigm that aligns KM to performance measures with validation of empirical evidences and results at both firm’s and industry’s levels.

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