

Evaluation of the solvent extraction organic phase in a uranium extraction plant

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(B.Eng. Chemical Engineering with Mineral Processing)



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Declaration

I, **Reinier Hendrik van der Ryst**, hereby declare that the dissertation entitled: **Evaluation of the solvent extraction organic phase in a uranium extraction plant**, which is done for the completion of a Masters Degree in Nuclear Engineering, is my own work.



R.H. van der Ryst

28 April 2011

Date signed

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Nomenclature

ADU	Ammonium di-uranate
CCD	Counter-current decantation
CCIX	Counter-current ion exchange
ISL	<i>In situ</i> leaching
IX	Ion exchange
LEU	Low enriched uranium
MSDS	Material safety data sheet
MW _e	Mega watt electric
NIMCIX	National Institute for Metallurgy continuous ion exchange
NWU	North-West University
PPE	Personal protective equipment
SEM	Scanning electron microscopy
SF	Separating funnel
SHE	Safety, health and environment
ST	Shaker table
SX	Solvent extraction
UOC	Uranium oxide complex

Throughout the text, mention is made of U_3O_8 as the cumulative term used to describe all the different uranium species in the various sections of the SX process. The analytical method used to analyse the samples produced during the experimental procedure reports the uranium assay as “converted to U_3O_8 equivalents”. These U_3O_8 equivalents include the presence and behaviour of any uranium in whatever species it is present. These uranium species include:

- $\text{UO}_2(\text{SO}_4)_2^{2-}$ and/or $\text{UO}_2(\text{SO}_4)_3^{4-}$ in the leach liquor and extraction circuit,
- $(\text{NH}_4)_2\text{UO}_2(\text{SO}_4)_2$ in the stripping circuit, and
- $(\text{NH}_4)_2\text{U}_2\text{O}_7$ in the precipitation circuit (also known as ammonium di-uranate or ADU).

For ease of reference throughout the text, mention is made of uranium species as U_3O_8 . The reader should be aware of the afore-mentioned species this refers to in the respective sections of the process.

In addition, the reader is informed of the use of the terms SO_4 and Fe as a cumulative description for any analysis that was conducted regarding the presence of sulfates and total iron content, respectively. Both these terms were used for ease of reference, but included in the literature is detailed information on which species were involved in each specific process step.

Abstract

Using kerosene as an aromatic organic diluent in the liquid-liquid separation process for the extraction of uranium in the solvent extraction section of the AngloGold Ashanti South Uranium Plant near the town of Orkney in South Africa, incurs a multitude of safety, health and environmental problems. A possible solution may be to replace the currently used aromatic-based organic diluent with an aliphatic-based organic diluent.

A range of aliphatic organic diluents were tested to determine the extraction efficiency of these alternative diluents, if they were to be applied to the process currently implemented by the AngloGold Ashanti South Uranium Plant. The aliphatic organic diluents under investigation were:

- Biodiesel – B-100
- Shellsol D70
- Sasol Wax SSX 150
- Sasol Wax SSX 210

The aliphatic diluent yielding the highest uranium extraction efficiency, and having the most desirable physical characteristics, was Sasol Wax SSX 210. Sasol Wax SSX 210 was selected to replace kerosene as the diluent in the solvent composition to conduct the next phase of the study.

The solvent's composition was then optimised to obtain a desirable solvent make-up containing the newly chosen aliphatic diluent, third-phase inhibitor and tertiary alkyl amine. The most favourable solvent composition was found to be; 5 vol.% Alamine 336 with 2 vol.% isodecanol and 93 vol.% SSX 210.

A third parameter, pH, was identified as an influencing factor on the overall efficiency of the process. A theoretical explanation for the influence that pH has on the process, confirmed by an experimental analysis, was examined to determine which pH characteristics contributed to the efficiency of the extraction process.

A final indication of the success of the newly implemented aliphatic solvent was determined via a precipitation simulation. The structure of crystals precipitated from the loaded strip liquor (OK liquor) was evaluated to ensure that the required product would adhere to product specifications.

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Above all I praise my Maker for the ability He installed in me, as well as the grace and perseverance He displays in guiding me to become the man He intended me to be, while giving me the time and means to better understand His wonderful creation while glorifying His name and serving His people.

1 Introduction

1.1 Uranium's history and future

To understand why this topic is relevant, we need to consider the history and predicted future of uranium. During the 1940s, the Manhattan project triggered a large-scale interest in nuclear technology, specifically with regards to the development of nuclear weapons. Uranium, the element that made this technology possible, was thought to be a limitless source of energy opportunities for the future. It was also the first metal recovered in significant quantities using solvent extraction (SX). After World War II, attention focussed on developing technologies that could be used to upgrade and purify uranium from low grade ores, and in 1957 the first commercial SX plant using amines was opened in the United States of America. Today, most of the world's uranium is recovered in hydrometallurgical circuits involving SX (Mackenzie, Undated).

As time passed and experience accumulated, it became clear that independence could be achieved from the dominating fossil fuel industry, and the focus shifted towards power generation via nuclear reactors (Höök, 2007). Currently, nuclear technology has a variety of peaceful and commercially important uses in, among other things, the health, medical, environmental and industrial sectors, and in electricity generation. Nuclear power plants are used to generate electricity by harnessing and controlling the energy from nuclear fission, and converting that energy to electricity for everyday use (Commonwealth of Australia, 2006). Relevant to this report is the importance of more efficient processing of uranium, aimed at producing fuel for nuclear reactors. This is to benefit its peaceful and commercially important uses, where nuclear fuel must be readily available.

1.2 Nuclear fuel

Nuclear fuel production is the driving force behind this project. The passing of the Kyoto Protocol led to a worldwide focus on the discovery, enhancement and optimisation of alternative, environmentally friendly and renewable energy sources. Effective extraction of uranium from the earth's crust is important when as - just like fossil fuel - radioactive (fissile) elements are limited natural resources. This is why there is a large financial incentive for the optimisation of nuclear fuel production

technology, with regards to maximum utilisation of fissile natural resources (like uranium) for the production of nuclear fuel. According to the World Nuclear Association (WNA, 2009), South Africa is focussed on commercial nuclear fuel fabrication, and the process of effective uranium extraction (mainly from gold-bearing ores and primary uranium-bearing ores) is therefore of the utmost importance.

It has been estimated that the nuclear fuel market has a sound supply of primary fuel (produced by current mining and fabrication processes) and a diminishing supply of secondary nuclear fuel (highly enriched nuclear material produced in the pre-Chernobyl era that has to be down-blended) to sustain the current projected consumption rate of uranium fuel to the year 2015. Meeting the global demand becomes more challenging thereafter, so more effective uranium processing techniques need to be addressed. This will facilitate a sharp increase in primary uranium supply, which is needed to meet increased market demand and to compensate for diminishing secondary supply stocks. Also important is maintaining investor confidence in nuclear power production, both for new mines and new reactors (Kidd, 2006).

1.3 Problem statement

Currently, the production rate of yellowcake at the AngloGold Ashanti South Uranium Plant is hindered by the plant's SX section. Although the extraction efficiency is 99.9%, this section of the plant poses a great safety risk to the rest of the plant, and to the health of employees and the surrounding environment. Kerosene (Engen laurel paraffin) is currently the diluent used in the extraction stages of the SX section. It is an aromatic compound with irritant vapours, posing a carcinogenic risk. In addition the vapour of kerosene is highly flammable due to its low flash point (ENGEN, 2008). The low flash point of kerosene (which comprises 93% of the solvent) may thus cause a gaseous explosion or liquid fire. There are several recorded incidents of SX fires (e.g. Stepnogorsk) which have led to an increase in insurance premiums for mine sites operating with a SX process unit (Carr et al., 2008). As a result, rigorous safety standards and fire-fighting equipment accompany the SX section, incurring additional costs which impact on the profitability of the plant. Kerosene is also an aquatic pollutant and, as the plant is close to the Vaal River, the use of kerosene poses a major environmental threat, which could further impact on the plant's profitability.

The storage, transport and replacement of chemicals used in the SX section at the plant is expensive. If a serious spillage or fire-hazard accident should occur, heavy fines, medical expenses and down-time could cripple plant operation. At the annual gathering of the global Nickel, Cobalt, Copper, Uranium and Gold Industries (Carr et al., 2008), specific attention was devoted to the topic of meeting the future challenges in the uranium extraction industry. Part of the discussion related to the chemicals required in SX and their associated hazards.

An increased demand for nuclear fuel throughout the world and the 2008 spike in uranium prices are substantial motivation for undertaking this study. The AngloGold Ashanti South Uranium Plant – the focus for this study - was constructed in 1978, and some equipment has reached the end-of-design life, raising the possibility of the plant undergoing an expansion project. Supplies of uranium are not unlimited, and thus the technology of uranium extraction needs to be optimised to ensure complete usage of available reserves. In addition, as uranium is only a value-adding by-product of the gold production section of the AngloGold Ashanti group, the upgrading or maintenance of the uranium processing plant should be financially justifiable.

Considering the abovementioned combination of problems and incentives, it was decided to investigate the substitution of the diluent currently in use with a more suitable diluent that would address these problems and assist in obtaining the incentives.

1.4 Aim and objectives

The aim of this study is to improve the safety factor for the SX section at the AngloGold Ashanti South Uranium Plant, without degrading the efficiency of the process by which uranium species can be extracted.

The objective is to find an improved solvent for the SX section of the AngloGold Ashanti South Uranium Plant that complies with stricter safety, health and environmental standards. This objective will be pursued by following this step-wise iterative procedure:

1. Select an alternative organic diluent to the kerosene currently used by investigating better safety, health and environmental (SHE) characteristics, and determining which of the alternatives renders the highest product yield/process efficiency.

2. Optimise the amount of extractant and third phase inhibitor used in the newly selected diluent.
3. While conducting the experiments, take note of possible influencing parameters that might cause the newly selected option to function less efficiently than the current option.
4. Prepare a sample that would represent the product from the SX section (the so-called OK Liquor) using the new diluent, and have the ammonium di-uranate (ADU) precipitated from it according to plant specifications. This would enable scanning electron microscopy (SEM) analysis of the product to evaluate the purity of the $(\text{NH}_4)_2\text{U}_2\text{O}_7$ crystals, such that any impurities or composition change can be investigated.
5. A brief discussion of the plant equipment currently used in the SX section will be conducted, with recommendations for future equipment upgrades based on the results and possible process difficulties that may be encountered using the different solvent.

1.5 Scope

There are various factors that have to be taken into account to ensure that this empirical investigation is well defined within the scope of the work to be done. Ore from the Noligwa, Moab Khotsong and Kopanang shafts is pumped as sludge to the AngloGold Ashanti South Uranium Plant near Orkney in the North-West province of South Africa. Because metallurgy is dependent on geographic and regional characteristics, the findings will be applicable only to the AngloGold Ashanti South Uranium Plant in South Africa, but similar process designs may consider these findings in order to conduct their own in-house research and investigations.

The scope of the laboratory work will be to obtain comparable efficiency data for the extraction, scrubbing and stripping steps of the SX section when using diluents with more desirable safety, health and environmental characteristics to kerosene. All other factors will be kept constant, and only the diluent will be varied in order to obtain an accurate quantitative assessment of the efficiency of the different diluents. Other factors that might change due to the use of a different diluent will be monitored, and further experiments will be conducted to enhance or rectify changes.

2 Literature review

The literature review for this dissertation can be represented by a priority pyramid diagram (figure 2-1). The diagram demonstrates the consecutive series of research steps in the literature review, which indicate the relevance of the different areas that have to be investigated to ensure that all the accumulating factors on the topic are fully covered, focusing on the impact thereof on the nuclear industry. At the base is a broad perspective, working upwards towards more detailed research with a product focus (obtaining high quality U_3O_8 for nuclear fuel production). The priority pyramid demonstrates the logical procession of the literature review.

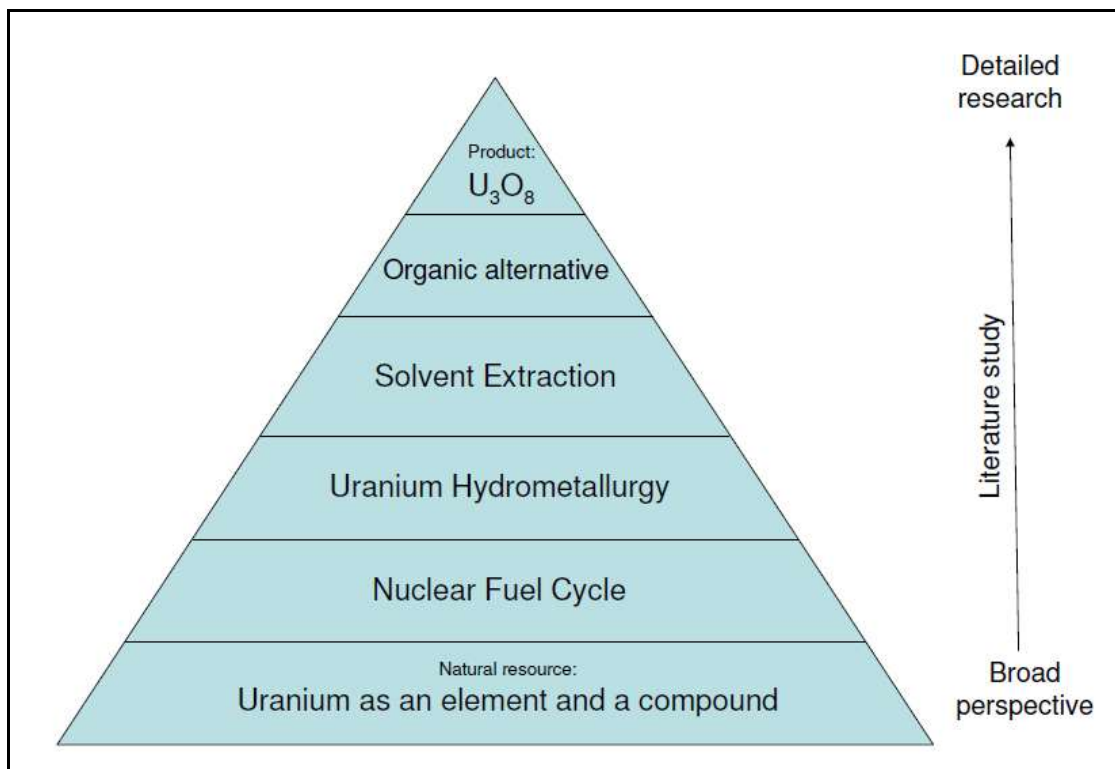


Figure 2-1: Literature review represented by a priority pyramid

2.1 Uranium as an element and a compound

In order to initiate the nuclear fuel cycle, maximum extraction of the natural uranium in uranium-bearing ore should be achieved, making it important to consider the characteristics of uranium as an element and as a compound. An article on uranium geology and mining explains that uranium is a fissile material (in this case a specific isotope of uranium called U-235) and the primary constituent of most nuclear fuels used globally to fuel nuclear reactors (Höök, 2007). Uranium can be found in many different compounds. The two most important oxidation states of uranium are the tetravalent $\text{U}(+IV)$ and hexavalent $\text{U}(+VI)$ states. Uranium dioxide is insoluble, and to create a soluble form, UO_2 must be oxidised from tetravalent to the hexavalent

oxidation state (Connelly, 2008). The most critical uranium oxides in the fuel fabrication process are triuranium octaoxide (U_3O_8) and uranium dioxide (UO_2) (produced from uranium hexafluoride). Both are solids with low solubility in water, and both are stable over a wide range of different chemical and environmental conditions. U_3O_8 is the most stable and the more common of these two compounds (Höök, 2007). The applicable uranium species that were encountered during this particular experimental investigation are sourced from the minerals uraninite, brannerite and coffinite, and the oxidant used is pyrolusite (MnO_2). Therefore the hydrometallurgical extraction process of uranium forms part of the overall nuclear fuel cycle.

2.2 Nuclear fuel cycle

The nuclear fuel cycle is the process by which uranium in mineral form (in the earth's crust) proceeds to be used as a nuclear fuel and eventually ends in permanent disposal as in figure 2-2 (Commonwealth of Australia, 2006).

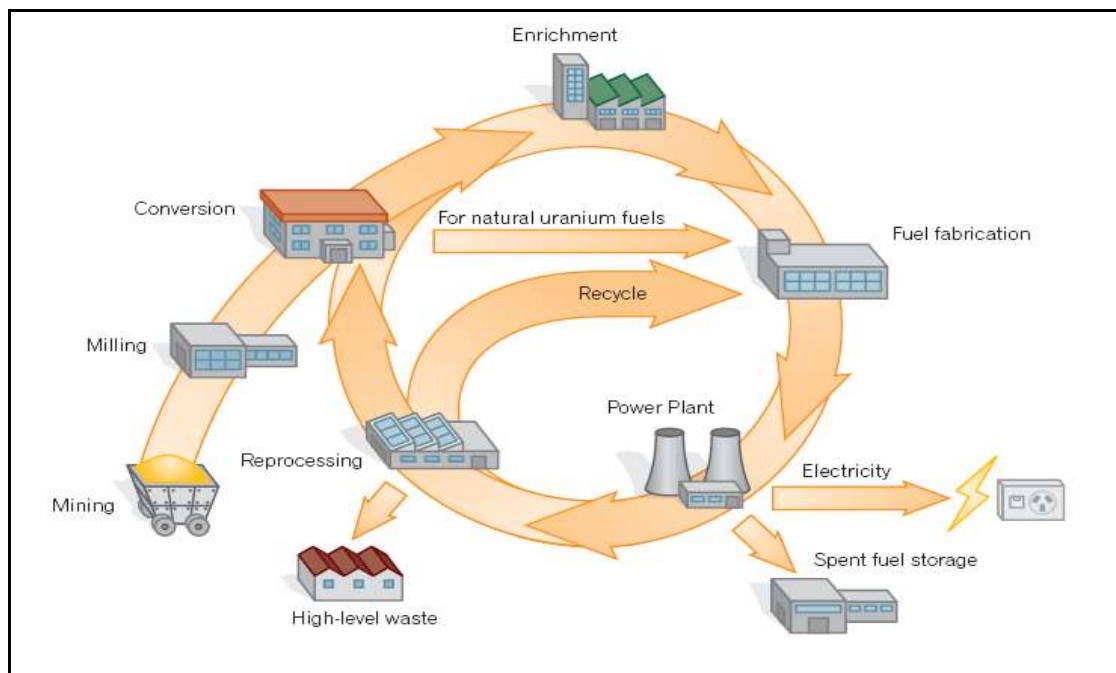


Figure 2-2: The nuclear fuel cycle (Commonwealth of Australia, 2006)

The steps in the cycle are described below.

2.2.1 Mining and milling

This section can also be referred to as the mineral processing section, because it includes the part of the nuclear fuel cycle that is the focus of this study, namely the

solvent extraction of ammonium di-uranate. For the discussion to be clearly understood, the steps preceding the SX section will be explained.

Depending on the geology and location of reserves, uranium-containing ore is mined using open-pit or underground techniques during the first step of the fuel cycle. During the second step in the cycle, the mineralised rock is ground and leached to produce a solution containing the dissolved uranium (Connelly, 2008). *In situ* leaching is another method of mineral extraction. It is a combination of the first two steps and is used in instances where the groundwater will not be adversely affected by these operations and where the geological formation contains mostly porous deposits like sandstone (Connelly, 2008). *In situ* leaching (ISL) relies on a technique that causes little surface disturbance, and no tailings or waste rock are generated. The ore is left undisturbed in its natural geologic position, while liquids are pumped through the deposit to recover the minerals through leaching. The product of this process, in which the previously separate steps are combined into a single process, is a solution containing dissolved uranium (Connelly, 2008).

For both methods of uranium mining, the method for the extraction of ADU from the solution containing the dissolved uranium (pregnant solution) is similar. The solution is treated to precipitate the ADU, which is ultimately dried and calcined to form uranium concentrate, conventionally referred to as U_3O_8 or yellowcake. Approximately 200 tonnes of concentrate are required annually to produce the fuel for a 1000 MW_e reactor (Commonwealth of Australia, 2006).

The hydrometallurgical processing of the mineral-containing ore is the focal point of the nuclear fuel cycle in this report.

2.2.2 Conversion

In order for uranium to be enriched, U_3O_8 must be purified and chemically converted to uranium hexafluoride. UF_6 can be a solid, liquid or gas, depending on the temperature and pressure. UF_6 is stored and transported as a solid in large secure cylinders. Transport costs can be up to five times those of transporting natural uranium, and shipping lines are reluctant to carry this material, as UF_6 is highly corrosive and chemically toxic when in contact with water. The international market for conversion is dominated by four companies supplying more than 80% of the world's uranium conversion services. The market has not seen new investment or

real production expansion and has been characterised by instability on the supply side (Commonwealth of Australia, 2006).

2.2.3 Enrichment

All nuclear power plants (except the CANDU reactor type) require fissile material that is more concentrated than the level present in natural uranium - in order to sustain a nuclear fission reaction in the reactor. U-235 is the only naturally occurring fissile nuclear isotope and in nature only one atom in every 140 will be U-235 (0.7%), the rest are U-238 atoms. This is true for most naturally occurring uranium, and it is therefore necessary to enrich the naturally occurring uranium by concentrating the percentage of U-235 in the uranium batch (Adelfang, 2007). Enrichment increases the U-235 proportion to 3–5%, producing low-enriched uranium (LEU) (Commonwealth of Australia, 2006). Enrichment is done commercially by the gaseous diffusion process or through the use of centrifuges. Both processes make use of the mass difference principle in the two uranium isotopes. UF_6 is used as the feed gas for both processes (Adelfang, 2007).

2.2.4 Fuel fabrication

The yellowcake from the AngloGold Ashanti South Uranium Processing Plant is sold to NUFCOR, which has strict product specification requirements. At NUFCOR the ADU is calcined to form UOC (uranium oxide complex). The purpose of the calcination process is to drive off the ammonia. The UOC is black, highly soluble in water, and is mainly comprised of UO_2 and U_3O_8 . The final fuel conversion, enrichment and pelleting operations are currently conducted in countries like France and the USA, which receive the UOC from NUFCOR. Optimising the percentage concentration of the uranium content in the yellowcake, as well as reducing iron and sulfate contents, is of utmost importance, and thus the SX section of the plant needs to perform according to specification and design.

Enriched uranium in the form of UF_6 gas is transferred to a fuel fabrication plant where it is transformed to UO_2 . UO_2 is a black powder that is pressed into small pellets that are sintered and ground to a precise shape. Hereafter, it is either loaded into fuel cladding (like zirconium rods) or used in other types of fuel arrangements. When the fuel assemblies have been compiled, the fuel is ready to be used in a power plant. Once its functional lifetime in the power plant has expired, the fuel is either stored in a spent fuel repository, or is reprocessed to re-enter the fuel cycle at the conversion step (as recycled fuel). If the spent fuel is not eligible for

reprocessing, it is disposed of in a high level waste repository (Commonwealth of Australia, 2006).

2.3 Hydrometallurgical process used by AngloGold Ashanti

The mining and milling step of the nuclear fuel cycle (as discussed above) includes the hydrometallurgical process which occurs at the case study site. Unless otherwise stated, information in this sub-section was obtained from AngloGold Ashanti, in collaboration with the management team of the AngloGold Ashanti South Uranium Processing Plant, and briefly summarises the current plant layout and operations.

AngloGold Ashanti's South Uranium Processing Plant produces uranium as a by-product of its underground gold mining operation. Plant operations comprise the collection of slurry from the Great Noligwa, Kopanang and Moab Khotsong gold mine shafts, which collectively produce about 52 000 kg U_3O_8 per month. The South Uranium Plant is currently undergoing the planning stages for upgrading or re-commissioning some of the older sections of the plant. The plant incorporates the following consecutive process sections:

1. Leaching
2. Counter-current decantation
3. Counter-current ion exchange
4. Solvent extraction
5. Precipitation

The focus of this report is a detailed investigation of the conditions and operations of the SX section.

2.3.1 Leaching

This section dissolves uranium present in the pulp. The pulp from the three gold mine shafts is fed to the Noligwa gold plant, from where it is pumped via two pipelines to the South Uranium Processing Plant. Here it proceeds to a cascade of 14 air-agitated pachuca tanks. The following are added in certain pachucas:

- The main lixiviant, concentrated sulfuric acid, is added first in the process to neutralise carbonate minerals, remove reducing agents, and to dissolve the uranium;

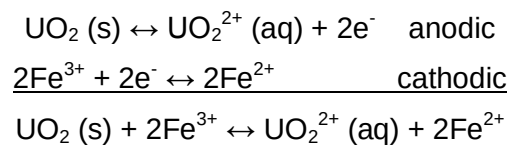
- Manganese dioxide (in the form of pyrolusite) is added to oxidise ferrous ions (Fe^{2+}) to ferric ions (Fe^{3+}). Ferric ions then oxidise tetravalent uranium to the hexavalent form which is soluble in acid;
- Steam is used to heat up the pulp to an optimum temperature of approximately 60°C .

The solution leaving the pachuca tanks contains the valuable dissolved uranium and is called the pregnant solution. The following reaction steps illustrate the chemical reactions that take place during this process step (AngloGold Ashanti, 2008).

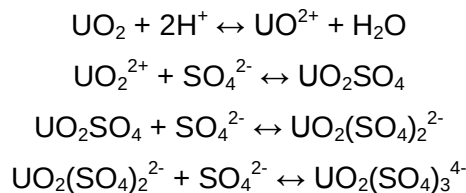
Reaction 1: Manganese dioxide oxidises the iron present in the pulp from the ferrous iron to the ferric iron



Reaction 2: Ferric iron oxidises the tetravalent uranium oxide to hexavalent uranium oxide



Reaction 3: Sulfuric acid ionises in solution to form sulfate, bi-sulfate and hydrogen ions



A project was launched by AngloGold Ashanti in collaboration with the University of Stellenbosch and Anglo Research, to develop a detailed kinetic leaching model and a diagnostic leaching tool for treatment of the Vaal River ore. The benefits of this research included better extraction and possibly reduced operating costs, both of which are potentially of great benefit to the industry. The project focused on sulfuric acid atmospheric leaching of uranium, and examining the nature of the uranium-bearing minerals (Lottering et al., 2007).

2.3.2 Counter-current decantation (CCD)

The next step is the application of a reverse leach process, which in short is the extraction of uranium before gold. The advantages in this step are a reduction in gold residue and lower pyrite values. Cyanide-soluble nickel and cobalt are also removed in this section, which benefits the ion-exchange section in the South Uranium Plant.

The South Uranium Plant's solid/liquid separation process differs from the conventional solid/liquid circuit in that CCD thickeners are used instead of drum filters. The purpose of the thickeners is to wash out the dissolved uranium (from the pulp through the action of counter-current solid/liquid separation) with a minimum dissolved uranium loss. There are six CCD thickeners (of which one serves as a clarifier) to which non-ionic flocculent is added at a controlled rate. Non-ionic flocculent is used to benefit the SX section, as it is an ion-exchange reaction-based process step. The pregnant solution (overflow of the thickeners) is pumped to the counter-current ion exchange (CCIX) adsorption columns. The overflow contains less than 60 ppm solids, as high solids content can cause excessive resin loss. The underflow from this section passes on to the gold processing plant (AngloGold Ashanti, 2008).

2.3.3 Counter-current ion exchange (CCIX)

The CCIX section reduces the volume of the pregnant solution by concentrating the uranium on resin. The volume of the solution treated in the CCIX section is reduced from 1000 m³/h to 30 m³/h. Uranium is upgraded from the leach liquor using ion exchange (IX) in National Institute for Metallurgy continuous ion exchange (NIMCIX) columns and is further purified using SX.

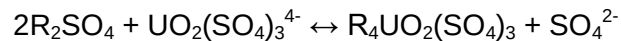
The CCIX section comprises five units, each consisting of:

- one adsorption column (wherein uranium transfers from the solution to the resin via ion exchange);
- one adsorption measuring chamber (receives loaded resin for quantity control);
- one regeneration chamber (for silica removal with caustic solution);
- one elution column (wherein uranium is removed from the resin);

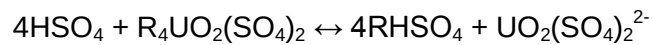
- one elution measuring chamber (for quantity control of concentrated eluate).

The uranium is eluted from the resin with a 12% sulfuric acid solution (known as the eluant), and the solution thereafter is referred to as the eluate. These reactions are illustrated as follows:

Reaction 4: Uranyl sulfate reacts with resin



Reaction 5: Sulfuric acid used in elution



The concentrated eluate is pumped to the SX plant for further processing. To replace the resin transferred out of the adsorption column, resin is transferred from the bottom of the elution column, via the elution column measuring chamber, into the top of the adsorption column. The resin transferred from the bottom of the elution column is known as stripped resin (AngloGold Ashanti, 2008).

2.3.4 Solvent extraction (SX)

This section purifies, concentrates and converts the uranium from the uranium-bearing solution into a suitable form for treatment in the ADU precipitation plant. This topic is the focus of the dissertation, and therefore a more detailed discussion is provided.

The SX process comprises five process units:

- Extraction: Uranium is transferred to a solvent phase in the extractors;
- Scrubbing: The solvent is washed with water in the scrub;
- Stripping: Uranyl sulfate is stripped from the solvent by a hydrolysis process and transferred to an aqueous phase. This aqueous phase is known as OK Liquor and is processed at the (ADU) precipitation plant;
- Regeneration: Cleans the stripped solvent before being recycled for re-use;
- After settler: minimises solvent loss.

The SX section is a Lurgi design from Germany. The uranyl sulfate anion complexes are the species extracted by amines. Unfortunately, the oxidising sulfuric acid leach that is carried out at a temperature of 58°C is aggressive and non-selective, resulting in many other species besides uranium being leached. The presence of these anionic species presents difficulties in the SX section. The organic-to-aqueous ratio for the continuous process at the plant is 1.1:1 (AngloGold Ashanti, 2008). Figure 2-3 (below) illustrates the process flow in the SX section.

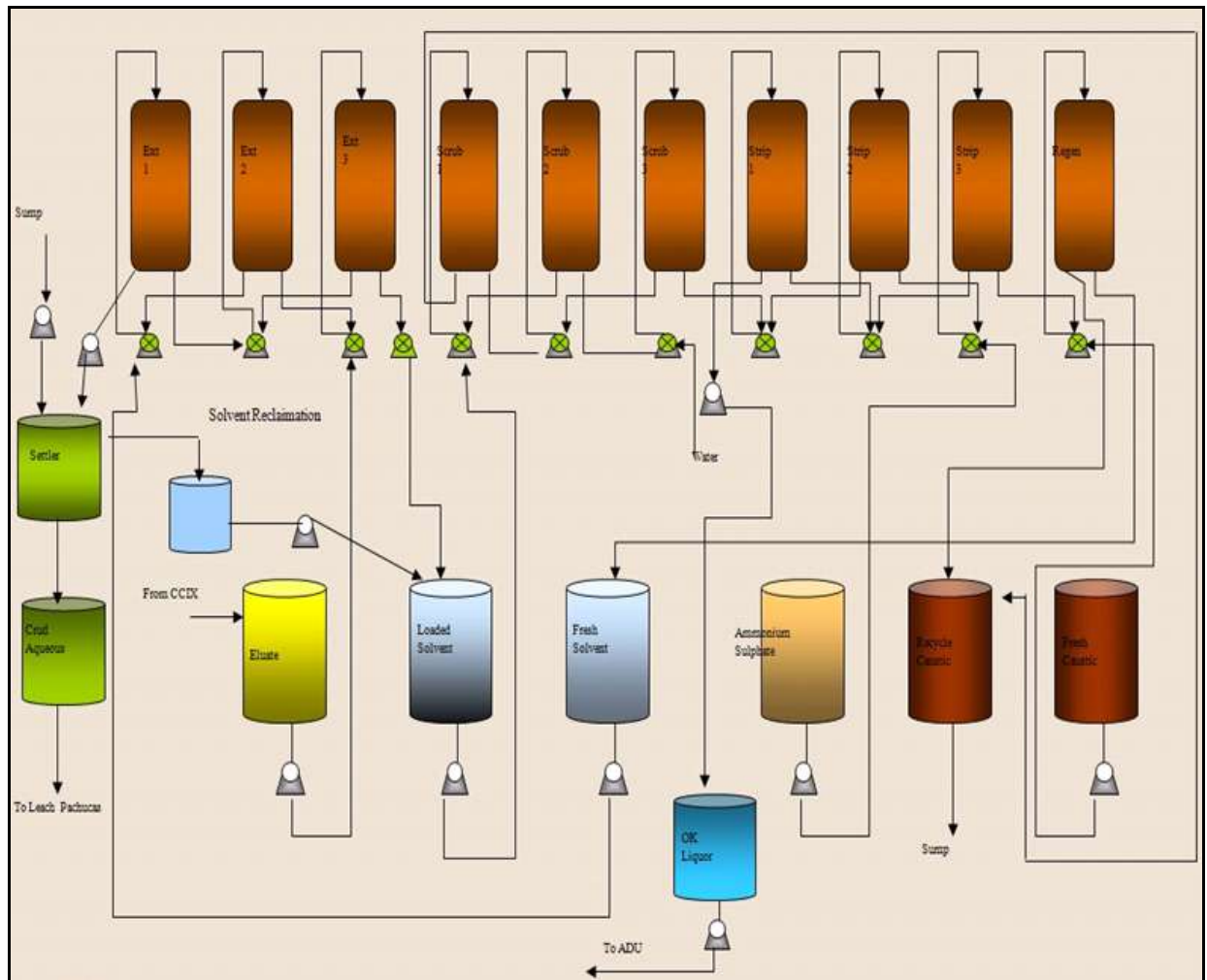


Figure 2-3: Diagrammatic illustration of the process flow of the SX section (AngloGold Ashanti, 2009)

The five major process units of the SX section are as follows:

2.3.4.1 Extraction

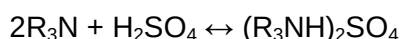
Extraction is effectively a purification step, as the extractant selectively extracts the uranyl sulfate. Concentrated eluate from the CCIX section passes counter-currently to a solvent phase through three extraction mixer-settlers. The solvent comprises three constituents:

- Isodecanol, 2% by volume. This is a third-phase inhibitor which aids the separation of the organic and aqueous phases;
- Alkyl amine, 5% by volume. This is the extractant used to collect the uranium. Alamine[®] 336 is used for this purpose. The chemical reaction between the anionic uranium complex and amine is reversible, depending on the pH value of the aqueous phase.
- Lighting paraffin, 93% by volume. This functions as a diluent and increases the bulk of the solvent, while reducing the viscosity of the mixture. Currently commercial kerosene is used.

Before entering the extraction mixer-settlers, the solvent is referred to as fresh solvent and after it has received the uranyl sulfate it is known as loaded solvent. Loaded solvent leaves the extraction mixer-settlers for further treatment in the scrub mixer-settlers.

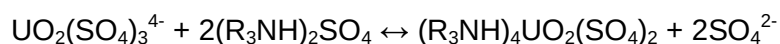
A three-stage extraction unit with mixers and settlers is provided to achieve good extraction efficiency. The Alamine 336 reaction with the acidic eluate is as follows:

Reaction 6: Alamine reaction



For the next equation the uranyl sulfate is selectively transferred to the barren organic phase by an ion exchange reaction:

Reaction 7: Extraction with solvent



The denuded eluate, known as the raffinate, becomes the recycle eluant (AngloGold Ashanti, 2008).

2.3.4.2 Scrubbing

There are two mechanisms for removing impurities from the loaded organic phase – physical and chemical. The physical process is referred to as washing, and includes the removing of species present as aqueous-phase droplets, which are physically entrained in the organic phase. The chemical removal of impurities is referred to as scrubbing and includes the use of water, the pH of which has a value that acts as a

reversal of the extraction equilibrium based on the pK_a of the extractant. Less strongly complexed species in the loaded organic phase (such as sulfate and ferric sulfate) can be removed by scrubbing.

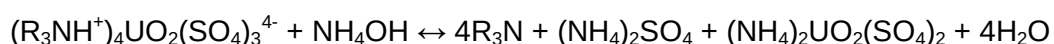
The physical removal (washing) dominates and thus is the only mechanism used in this step. Due to plant terminology, reference is made to scrubbing instead of washing (which would be technically more correct).

In the three scrub mixer-settlers, the loaded organic phase passes counter-currently to water. The purpose of the water is to remove a maximum quantity of any impurities, such as iron and sulfates, that were picked up in the extraction mixer-settlers.

2.3.4.3 Stripping

The purpose of the strip mixer-settlers is to convert the uranium into a suitable form for further treatment in the ammonia precipitation plant. The scrubbed loaded solvent passes through to three strip mixer-settlers and passes counter-currently to the stripping reagent, which is an ammonium sulfate solution in an aqueous phase. Additional input of an ammonium hydroxide solution is used to raise the pH value progressively, in order to hydrolyse the amine uranium complex and transfer the uranium into the aqueous phase. Stripping chemistry is the use of hydrolysis by using ammonium hydroxide. Thus uranyl sulfate is stripped from the loaded solvent and is transferred to the aqueous phase through the following reaction:

Reaction 8: Stripping of the OK Liquor



The new aqueous phase is referred to as OK Liquor and is sent to the ADU precipitation plant for further treatment. Excess ammonium sulfate is periodically bled from the circuit (AngloGold Ashanti, 2008).

2.3.4.4 Regeneration

The stripped solvent flows to the regeneration mixer-settler for removal of any excess anions and organic cation exchangers. This is necessary to prevent an accumulation of these poisons present in the solvent. The solvent is treated with sodium hydroxide and sodium carbonate solution, before being returned to the fresh solvent storage section.

2.3.4.5 Solvent recovery

The after settler is used to recover any expensive solvent that has become entrapped in the spent eluant leaving the extraction mixer-settlers.

2.3.5 Precipitation

The OK Liquor containing the uranyl sulfate is at this stage precipitated with ammonia gas, after being heated in an Alfa-Laval heat exchanger. The uranium precipitates out in the form of ADU. Together with the ammonium sulfate solution, the precipitate is pumped to a thickener. The underflow passes through a two-stage centrifuge system, firstly to wash out any impurities, and secondly to increase the relative density so that its bulk is reduced for transport to NUFCOR. The ADU produced contains $\pm 38\%$ U_3O_8 . The purity of the uranium is approximately 98% after calcining at 490°C (AngloGold Ashanti, 2008).

2.4 Lime slaking process

Slaked lime is used to neutralise the pulp at the Gold Plant before the cyanide leaching process, to prevent the formation of cyanide gas. The calcined lime is delivered by railway trucks in a crushed form, which is approximately 19 mm in diameter, with available lime content approximately 88%. Slaking is the disintegration of the calcined lime by the addition of water to produce a lime pulp. The contact time in the compartments - which are fitted with mechanical agitators - assures complete slaking because of the efficient mixing of the water and unslaked lime (AngloGold Ashanti, 2008).

2.5 Solvent extraction

2.5.1 Basic concept explanation

The process of transferring a compound (solute) between two immiscible liquid phases (in this case an organic and an aqueous phase), is called solvent extraction. If the solute is dissolved in the aqueous phase (a water-based liquid) and the solution is brought into contact with the organic phase (immiscible liquid solvent), then a part of the solute is transferred to the organic phase by a force called the chemical potential. This is a chemical-physical process. Uranium extraction in the SX section is an ion-exchange reaction involving many anionic species. It is neither highly selective nor as pH-dependent as the chelation and solvation processes (van Rensburg et al., 2009). The commercial unit employed to perform SX is known as a

mixer-settler configuration and on laboratory scale it is termed a shake-out test (separating funnels mounted on a shaker table). Inside the equipment a mixing (agitation) and a coalescence step (settling by gravity) can be observed. During the mixing stage of the experimental process the mass transfer of the solute between the two liquid phases occurs.

The rate of coalescence is highly dependent on the viscosity, density and interfacial tension of the liquids and the drop size of the dispersed phase. When the agitation of the liquids is stopped, the rate of transfer of solute gradually slows down and keeps diminishing until equilibrium is reached (after extended contact time). The time necessary to reach 90% of the equilibrium is characteristic of a given solute/solvent system, since equilibrium will never reach 100%. This time is a function of the product of the mass transfer coefficient and the interface area between the liquids: ($k_t \times a$). The equilibrium that is spoken of at 90% solute transfer is characterised by a distribution coefficient D . This coefficient can be defined as the concentration ratio of all species of solute in the organic phase, to all the species of solute in the aqueous phase. D is dependent on the initial concentration of the solute and the concentration of other components in solution. To ensure a thorough transfer of solute from the aqueous to the organic phase, the liquid phase ratio of solvent to aqueous solution should be as high as possible (Halwachs, 2009).

Large industrial applications of SX usually have more than one mixer-settler unit (a higher number of stages might be required according to theoretical calculations). This occurs especially when the distribution coefficient is low or close to one. The repetition of mixing and settling can provide a higher concentration and improved purity of the solute in the organic phase (Halwachs, 2009).

2.5.2 Possible future developments

Conventional mixer-settlers were the initial equipment preferred for uranium SX in earlier plant designs. A number of alternative designs were, however, introduced in response to increased demand for improved product quality and more cost competitive methods. One of these innovations is the Krebs “double deck” design which offers a smaller footprint area, a reduced organic inventory and is especially suitable for indoor use. Less popular designs include the Davy combined mixer-settler, the IMI circular settler, the Lurgi plate settler and the Kenics inline mixer. In recent years some attention has focused on the use of pulsed columns, especially in the case of uranium, because of the fast ion-exchange kinetics involved in the

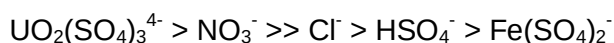
extraction process (Taylor, 2007). It is also likely that pulsed columns will continue to be considered as an alternative to mixer-settlers. Bateman columns have grown in popularity and have been installed at Dominion Uranium Project (Bateman, 2007).

2.6 Solvent composition

The solvent used to contact the fresh eluate consists of a specific volume percentage composition of the extractant, diluent and third phase moderator.

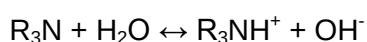
2.6.1 Extractant

The mechanism used for uranium extraction falls in the ion-exchange class. There are a number of extractants that can be used to recover uranium. The only extractants that have found widespread commercial acceptance are, however, the tertiary and quaternary amines and the organic phosphates. SX recovery of uranium is restricted to acid leach solutions. By far the most widely used extractants for uranium are the tertiary amines, specifically the C8-C10 symmetrical amines. In the case of the South Uranium Plant, Alamine 336 is used. Under typical acid leach conditions almost all of the uranium is present as the $\text{UO}_2(\text{SO}_4)_3^{4-}$ complex and uranium SX plants are designed based on a theoretical maximum loading of 1.2 gram U per 1 vol. % Alamine 336. As there is between 3 and 5 g/L uranium species in the eluate, the solvent must contain at least 5 vol.% Alamine 336. In practice the theoretical maximum loading is not attained due to the presence of competing anions in the leach liquor. Ion-exchange extractants are non-selective and, although the uranyl sulfate anion complexes are strongly extracted by tertiary amines, other anions will also be extracted. The order of selectivity for some anions is (Mackenzie, 1997):



Due to the lone pair of electrons on the nitrogen atom, alkyl amines are strongly basic towards water. The acid base reaction of a tertiary amine with water is given below:

Reaction 9: Protonation



This protonation reaction must take place in order for the tertiary amine to react with anions in the system. The solubility of the counter ion in the system (in this case the

sulfate ion) will influence the degree of protonation. The degree of protonation can be calculated using:

$$\begin{aligned}\% \text{Protonated} &= 100 / 1 + \text{antilog}(\text{pH} - \text{pK}_a), \text{ with} \\ \text{pK}_a + \text{pK}_b &= 14, \text{ and} \\ K_b &= [\text{R}_3\text{NH}^+] [\text{OH}^-] / [\text{R}_3\text{H}], \text{ from reaction 9.}\end{aligned}$$

Alamine extractants are almost completely protonated at pH values below 6, and for many acid leach solutions the pH is well below 6 (as in this study). Thus protonation takes place almost instantly when the amine contacts the leach solution (Mackenzie, 2005). The effect of pH on the loading of uranium species on Alamine 336 is shown in figure 2-4 (Mackenzie, 1997). Due to the weak basicity of tertiary amines in this system, stripping commences at an approximate pH of 3. The protonation of the amine increases as the pH is lowered, and this increases the amount of U_3O_8 equivalents that will be extracted.

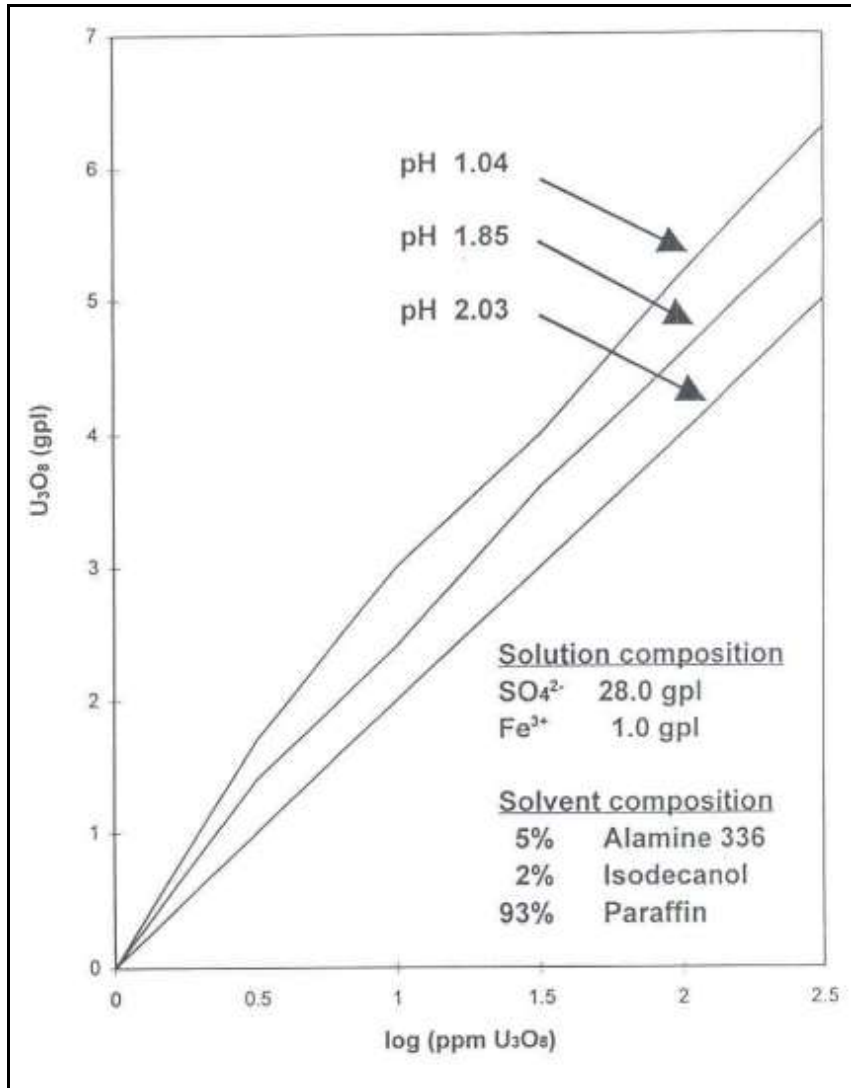


Figure 2-4: The effect of pH on the loading of U_3O_8 on solvent (Mackenzie, 1997)

In figure 2-4 the unit gpl refers to grams per litre, which is denoted as g/L throughout the rest of the text.

2.6.2 Third-phase inhibitors

To prevent third-phase formation in practical extraction systems, a modifier (higher alcohols like isodecanol) is used to improve the solubility of the tertiary amine in the diluent.

The uranium-amine complex formed from the C8-C10 tertiary amines (extractant) has limited organic solubility in the 0-20% aromatic diluents typically used, and a third-phase inhibitor is added to the organic phase to improve this solubility. Isodecanol is the usual third phase inhibitor used, and it is added at about 50-60% of the amine concentration. The presence of isodecanol can make phase separation of

the mixed organic more sensitive to dissolved and precipitated silica. This is presumably due to a hydrogen bonding linkage between the silica and the alcohol OH group. Note also that isodecanol is much more soluble in water than amine (Mackenzie, 1997).

Isodecanol ($\text{CH}_3(\text{CH}_2)_9\text{OH}$) oxidises in the presence of air and has a high redox potential to aldehyde, carboxylic acid and eventually primary alcohol which will result in poor coalescence. An alternative to isodecanol as a third-phase inhibitor is to add a high aromatic content diluent (+90% aromatic) to increase the total aromatic content of the diluent to 36-40%. Such high aromatic diluents are not subject to bacterial decay, and it is possible that they may be more tolerant to dissolved and precipitated silica than the diluent-isodecanol mixtures. However, high concentrations of aromatics can further increase environmental and health problems. As an alternative, iso-tridecanol ($\text{CH}_3(\text{CH}_2)_{12}\text{OH}$) can be used. While iso-tridecanol has the benefit of being inherently more stable and has lower solubility in both the aqueous phases, the increased price may be a deterring factor (van Rensburg et al., 2009).

2.6.3 Diluent

In many cases, the role of the diluent on the chemistry of a system is minor, and the choice of diluent is decided by the diluent's physical properties. A diluent used for amine extraction of uranium should have the following characteristics:

- Be insoluble in the aqueous phase;
- Solubilise the extractant;
- Solubilise the extractant-metal complex;
- Not adversely alter the extraction and strip equilibria;
- Have a flash point significantly (at least 30°C) higher than the operating temperature;
- Have a low viscosity;
- Be chemically stable;
- Have good phase separation properties;
- Have low entrainment;
- Not form crud and be tolerant to crud;
- Have acceptable cost;
- Be non-carcinogenic.

2.7 Aliphatic diluents versus aromatic diluents

The aim of this study was to investigate alternate diluents for use in the in SX circuit of a uranium extraction plant, which would offer better HSE characteristics without compromising on performance. Aliphatic diluents are considered to be better than aromatic diluents in this regard.

A major consideration in whether an aliphatic or aromatic diluent should be used began when uranium processing plants reported a certain amount of degradation of the organic phase. This had a detrimental effect on the kinetics, as well as loading and phase separation times. As a result, extensive crud formation, poor stripping efficiency and excessive organic entrainment were noted. Organic-phase breakdown products were thought to be the cause of problems in the strip section of the SX plant. It was recommended that an aliphatic diluent should be used as well as the addition of butyl hydroxyl toluene (BHT) as an antioxidant, to prevent organic phase breakdown (van Rensburg et al., 2009).

When considering the basic chemistry of the two groups of diluents, a fundamental difference can be seen in the bonding structure. Aromatic hydrocarbons contain benzene rings which are cyclic and conjugated, whereas aliphatic hydrocarbons can be joined together in straight chains, branched chains, or non-aromatic rings (in which case they are called alicyclic).

The nature of an organic diluent used in a SX system affects the extent of metal extraction and the phase separation behaviour. Processes for solvent extraction of metals have been developed for specially selected combinations of extractant and diluent. To prevent third-phase formation in practical extraction systems, a modifier (especially higher alcohols) is used. Isodecanol is part of the organic phase and functions as an essential phase modifier, as it improves the solubility of the tertiary amine in the diluent. The diluent is not only a carrier for the extractant and extracted metal complex, but is also a participant in the extraction process. The effect of the diluent is essentially an organic-phase reaction or interaction due to at least one of following two factors:

- Interaction with the extractant molecules, which affects the activity of the extractant and changes the extraction performance of the extractant;

- Interaction with the extracted metal complex, which may change the composition of the complex through coordination and/or substitution of the diluent molecules.

The distribution ratio is directly affected by whether a polar or non-polar hydrocarbons diluent is used (Komasawa et al., 1984). The amount of uranium that can possibly be extracted is directly impacted by the aromatic content, the dielectric constant and the polar nature of the diluent. A faster phase separation can be achieved with diluents with relatively high dielectric constants and dipole moments. This result can be explained in terms of the destruction of micelles, the formation of mono-layers and other interfacial phenomena. Increasing the temperature at which the extraction process operates could improve the phase separation characteristics considerably, whereas the extraction only improves slightly (Bailey and Mahi, 1987).

With or without BHT antioxidant, the aliphatic diluent has far fewer deleterious effects after oxidation than with a diluent containing a higher portion of aromatics (van Rensburg et al., 2009). To date, the aliphatic diluent has not been shown to provide any significant changes in the operation of a SX facility. A number of factors, such as strip efficiency, crud formation at low temperature, and bacterial growth may or may not be linked to changing the diluent. There is some contradictory evidence on whether aromatic diluents should or should not be used, but this becomes largely irrelevant when the antioxidant is added to the diluent.

2.8 Advantages of aliphatic diluents

Aliphatic diluents are preferred in SX circuits containing metals which promote the oxidation of the diluent, in SX plants that are health and safety conscious, and those that prescribe to a low level of aromatic emissions for environmental reasons.

Because of the synthetic production process of unique normal alkanes, aliphatic diluents have low aromatic content, negligible sulfur levels and are practically odourless and colourless. These properties render a diluent that is environmentally friendly, and this sets them apart from the liquid paraffins derived from crude origin (aromatics).

Aliphatic diluents have proved to be preferable for the extraction of cobalt or for circuits which contain significant amounts of cobalt and nickel, making them susceptible to diluent oxidation. Diluent oxidation causes the introduction of

carboxylic acids and the formation of sodium carboxylates into the organic phase. The presence of carboxylic acids causes a significant falloff in the Co/Ni separation factor. Sodium carboxylates interfere with the phase break, causing drastic deterioration over time, which eventually results in the failure of the circuit. Diluent oxidation in the absence of an anti-oxidant is much faster for an aromatic diluent than for an aliphatic diluent. Thus, aliphatic SX diluents are the preferred diluents in SX circuits in which the metals present promote the oxidation of the diluents.

Aliphatic diluents are used in plants where low aromatic levels in diluents are preferred for health reasons and due to the environmental limits placed on total aromatic emissions. The inert nature of aliphatic diluents, and the low aromatic content makes them suitable for use in such circuits. The aliphatic range is free of poly aromatic compounds, which are known carcinogens. (Sasol Wax, 2009^a)

2.9 Alternative diluents

A study was conducted into the available range of alternative diluents (currently considered by other companies) that could function properly for uranium extraction. A shortlist was compiled according to merit with regards to environmental, health and safety benefits - with a secondary consideration being functionality, efficiency and cost effectiveness.

2.9.1 Diluent range

B-100 Bio-diesel: EECO Fuels (Biodiesel Technologies) were contacted and they recommended this product due to its high flash point (180°C) and low sulfur content (109 mg/kg). No known experimental work has been conducted on this combination of diluent, extractant and third-phase inhibitor (EECO Fuels, 2008).

Sasol Wax SSX 150: This is synthetic paraffin produced by Sasol Wax (South Africa), a division of Sasol Chemical Industries. It behaves very similarly to the kerosene currently in use by the South Uranium Plant, but has slightly better SHE characteristics. The aliphatic SSX diluents are preferred in SX circuits of plants that are SHE conscious. This product was chosen because of its low aromatic content which is less than 0.3 vol.%, kinematic viscosity of 1.19 cSt at 40°C, and its flashpoint of 45°C. (Sasol Wax, 2009^b).

Sasol Wax SSX 210: Recommended from the above-mentioned company specifically for uranium extraction. The beneficial properties of this diluent include: an aromatic content less than 0.1 vol.%, a sulfur content less than 1 mg/kg, a kinematic viscosity of 1.9 cSt at 40°C, and a flash point of 88°C (Sasol Wax, 2009^b).

Shellsol D70: A product of Shell Chemicals, more readily applicable for cobalt, nickel and zinc extraction, because it is an aliphatic compound with a flash point of 77°C (Shell Chemicals, 2005).

Refer to the Material Safety Data Sheets (MSDS) in Appendix A for a more complete overview of the selected diluents.

3 Experimental

3.1 Experimental procedure validation

The experimental setup and apparatus used are commonly referred to as a *shake-out test* (Rydberg et al. , 2004). It is widely used in the industry (laboratories of mineral processing plants) and in the academic world. The setup and procedure make use of well-known apparatus, electronic equipment and analysis methods. The method of simulating the process conditions in the SX section of the plant was recommended by the AngloGold Ashanti Vaal River Laboratory. Confirmed use of this experimental procedure on selective extraction is mentioned by Qin et al. (2008). This setup and procedure were previously used by the AngloGold Ashanti Vaal River Laboratory to conduct experiments in the same research area. Although the shake-out test setup varies considerably from the mixer-settler setup, it is deemed an accepted laboratory method for mixing immiscible fluids.

3.2 Safety precautions

Certain safety criteria had to be met while conducting the experimental procedures. The necessary personal protective equipment (PPE) was worn inside the laboratory. The chemicals used were researched with regards to safety and the required MSDS are included in Appendix A.

As the eluate sample (which is acidic) was obtained from the South Uranium Processing Plant and would have to be handled during the experimental procedure, a required two-day theoretical safety induction was completed at the plant.

The safety officer at the AngloGold Ashanti laboratory in Orkney co-ordinated a walk-through safety induction of the laboratory premises, as well as a detailed safety briefing on the section of the laboratory where the SX experimental test bank is situated. A safety representative was assigned to the research group. The safety representative could be contacted at all times and was assigned as an observer of all research activities, to ensure that the group operated within the required safety codes and procedures followed in the laboratory.

3.3 Experimental apparatus

The following is a list of apparatus and equipment used to conduct the experiments:

- Labcon shaker table: SPL 15 with UPF 55
- 500 mL separating funnels
- Erlenmeyer flasks
- Measuring beakers
- Measuring flasks
- Measuring cylinders
- pH meter
- Magnetic stirrer
- Burette
- Pipette
- Retort stand
- Extraction cabinet.

3.4 Chemical reagents

In selecting candidate diluents for the experimental procedure, it was decided that the aromatic diluent in use, kerosene (containing 10–45% aromatics), should be replaced with aliphatic diluents with a much lower aromatic fraction (see sections 2.7.1 and table 4.1).

The following is a list of reagents used to conduct the experiments:

- Kerosene – received from the South Uranium Plant
- Biodiesel – B-100
- Shellsol D70 – Ordered from ChemQuest
- Sasol Wax SSX 150 – Ordered from ChemQuest
- Sasol Wax SSX 210 – Ordered from ChemQuest
- Ammonium sulfate – crystals: 99% purity, 130g/L solution
- Ammonium hydroxide – liquid: 25% solution
- Alamine 336 – received from the South Uranium Plant
- Isodecanol – received from the South Uranium Plant

3.5 Constant empirical parameters

The reaction kinetics of the experiments is accepted as being fast and consistent. A standard contact time and contacting mechanism was therefore used during each experiment. The kinetics of extraction via ion-exchange mechanisms is much faster than for a chelation mechanism (Mackenzie, 1997). Therefore, the decision was made to simulate a mixer-settler unit using a shaker table and separating funnels with a short contact and residence time. A contact time may be as low as 45 seconds for complete extraction and stripping (Mackenzie, 1997). An article on uranium and cobalt SX (van Rensburg et al., 2009) also suggests a short contact time. Recommendations were considered from researchers with experience of experiments run on similar projects. A contact time (kinetic constant) of 180 seconds and an agitation revolutions setting of 230 rpm were decided upon.

Verbal communication with the plant manager of the AngloGold Ashanti South Uranium Plant confirmed that 99% of the extraction of the uranium sulfate complex was achieved during the first stage of the extraction section (du Plessis, 2009). Only one stage was therefore used in the experimental setup. All the experiments were carried out at ambient laboratory temperature ($18 \pm 2^\circ\text{C}$). The eluate used at the start of every experiment was decanted from an agitated representative sample obtained from the South Uranium Plant.

The organic-to-aqueous ratio for the continuous process at the South Uranium plant is 1.1:1, but because of equipment restrictions, the experimental procedure was carried out at an aqueous-to-organic ratio of 1:1.

3.6 Experimental procedures

Four main experimental procedures were carried out.

3.6.1 Experimental procedure 1: Diluent selection

The purpose of experimental procedure 1 was to select the diluent with the most favourable physical properties, whilst yielding a favourable extraction efficiency of the respective uranium species.

The diluent used in the simulation of the SX process was varied between the four alternative researched options: Shellsol D70; SSX 150; SSX 210; and Bio-diesel B-100. The same diluent as used in the conventional plant (kerosene) was used to

carry out an independent experimental test run to establish a result that could be compared to the known industrial behaviour and result. This would also serve as an indication of the validity of the experimental setup and the accuracy of the results yielded by the experimental setup. The percentage composition of the solvent, as currently used in the industrial plant, was used. However the organic-to-aqueous ratio for the continuous process at the South Uranium plant is 1.1:1. Because of equipment and reagent restrictions (discussed in the following paragraph) the experimental procedure was carried out at an organic-to-aqueous ratio of 1:1.

The amount of organic diluent received for research purposes from ChemQuest laboratories was restricted, and thus the organic diluents that would be varied for different experiments had to be used sparingly. The laboratory analysis required a certain volume of sample to be generated by each experimental run to conduct each separate analysis. The separation funnels could only accommodate a 500 mL volume. The minimum amount of sample required for each analysis could only be produced if the organic-to-aqueous ratio could be taken as 1:1 for a restricted volume of 500 mL. This adaptation to accommodate laboratory restrictions did not influence the decision-making process, since the type of analysis method used to evaluate between the alternative diluents would be qualitative.

3.6.2 Experimental procedure 2: Solvent composition

The purpose of experimental procedure 2 was to empirically determine an optimum solvent composition comprised of the diluent, third phase inhibitor and extractant. The diluent that was selected on the basis of the results obtained in experimental procedure 1 was selected to conduct the SX simulation. The process variable that was changed was the percentage composition of Alamine 336 (the extractant), whilst the percentage isodecanol (which is the third-phase inhibitor) in the solvent composition was kept at a constant volume percentage of the extractant.

3.6.3 Experimental procedure 3: pH investigation

The purpose of experimental procedure 3 was to obtain an explanation and possible solution to the apparent pH instability during the stripping stage.

During the process of raising the pH during the stripping stage of the SX process, a characteristic of the solution was encountered that will have a large influence on the practical implication of the process. This is especially with regards to new equipment (pulsed column) that has been considered as a replacement for the mixer-settler

setup in order to obtain better efficiency in the SX section of the plant. A short theoretical investigation (included in this section) and valued opinions from industry specialists were used to come to a conclusion regarding the influence of the pH instability on the selection of potential future technology for the plant.

3.6.4 Experimental procedure 4: Precipitation evaluation

The purpose of experimental procedure 4 was to determine if the newly selected diluent and the optimised composition of the solvent would yield OK Liquor that would precipitate according to the method currently used by the plant.

A single precipitation trial was conducted with ammonia gas to obtain ADU precipitate in order to evaluate the crystal structure.

3.7 Methodology: Experimental procedure 1

1. Preparation:

- a. 1 L of the solvent solution was prepared with the composition:
 - 2 vol.% isodecanol
 - 5 vol.% alkyl amine (Alamine 336)
 - 93 vol.% diluent (which is varied in each case)
- b. A bench with three 500 mL separating funnels (SFs) was set up as shown in figure 3-1. The three funnels were manned by the three researchers and all the activities were done simultaneously by them to ensure the experiments were triplicated. This enabled calculation of a standard deviation in the three samples per experimental run, and the data could be evaluated in a statistical computer simulation package to ensure data reliability. The statistical data can be viewed in Appendix G of this report.

2. Extraction/Loading:

- a. 250 mL of fresh eluate (from the CCIX plant) was added to 250 mL of the solvent. Samples from both these solutions were taken for analysis.
- b. The three SFs were placed on the shaker table (ST) and shaken for three minutes at 230 rpm, as represented in figure 3-2.



Figure 3-1: Bench containing three SFs for triplication of the experiment

- c. The SFs were placed on the bench simultaneously. The time taken for complete phase separation, as shown in figure 3-3, was recorded (the time it took for two of the three SFs phases to separate completely was taken as the settling time).



Figure 3-2: Shaker table with three separating funnels

- d. The aqueous phase (raffinate) was decanted and sent for analysis (250 mL).
 - e. 100 mL of the loaded organic was decanted to be analysed.
3. *Scrubbing*:
- a. 150 mL demineralised water (the same volume as the loaded organic that remained in the SF) was added to the loaded organic for the scrubbing process.
 - b. The three SFs were placed on the shaker table and shaken for 3 minutes at 230 rpm, to remove impurities.
 - c. The SFs were placed in the bench and the phase separation times were monitored and recorded.



Figure 3-3: Phase separation in the separation funnel

- d. The spent scrub water was decanted and sent to be analysed.
4. *Stripping*:
- a. 150 mL ammonium sulfate (99% purity, 130 g/L) was added to the scrubbed organic.
 - b. The SFs were shaken for 3 minutes at 230 rpm.

- c. The SFs were placed in the bench and the time taken for the phases to separate was recorded.
- d. A burette containing ammonium hydroxide (25% solution) was clamped to a retort stand above a measuring beaker. The beaker was placed on a magnetic stirrer and a rotation magnet was placed inside the beaker. A pH probe connected to a pH meter was placed in the beaker. This equipment setup is shown in figure 3-4.



Figure 3-4: Stripping experimental procedure setup

- e. The initial pH value and the final pH value were recorded. The volume of ammonium hydroxide used for this hydrolysis process was also tabulated.
- f. The phases were allowed to separate when the correct pH conditions were reached, and the aqueous phase was decanted and sent for analysis. The organic phase was also decanted and sent for analysis. Figure 3-5 illustrates the examples before and after the stripping procedure.



Figure 3-5: Sample before (left) and after (right) stripping

Each of the five diluents was experimented with in exactly the same manner. This was to ensure that simulation of the process conditions in the laboratory was as constant and reproducible as possible for the three samples that were prepared.

3.8 Methodology: Experimental procedure 2

The diluent that performed the best (based on overall judgement of the improved physical properties and efficiency of the different diluents) was chosen for the next stage of the experimental process.

The procedure steps as mentioned in experimental procedure 1 were repeated, the solvent's composition (volume percentage of different constituents) was, however, varied for each experimental run. The different samples' compositions are presented in table 3-1.

Table 3-1: Solvent composition of experimental procedure 2

Sample	SSX 210	Alamine 336	Isodecanol	Total
	vol.%	vol.%	vol.%	vol.%
1	95.8	3.0	1.2	100
2	93.0	5.0	2.0	100
3	90.2	7.0	2.8	100
4	87.4	9.0	3.6	100
5	84.6	11.0	4.4	100

The Alamine 336 content was varied between 3% and 11% for each sample, whilst the isodecanol volume was taken at 40% of the volume of the Alamine 336. The remaining volume percentage was filled to 100% with the preferred diluent: Sasol Wax's SSX 210.

The five samples were separately experimented with through the procedure steps of experimental procedure 1, with only the solvent [mentioned in procedure step 1: Extraction/Loading: (a)] being replaced with solvent of the above-mentioned composition. The other experimental procedures and reagents replicated the procedures of experimental procedure 1.

3.9 Methodology: Experimental procedure 3

During process step 3, while conducting the stripping procedure, the addition of ammonium hydroxide (NH_4OH) to the first sample did not seem to have a noticeable effect on its pH (after the addition of the first few drops). Thus the NH_4OH was added at a higher rate until the required pH was reached. However the pH did not stop at the level attained when the addition of NH_4OH was halted, but kept on increasing in larger intervals until eventually the uranium in the sample precipitated. The sample was discarded. The physical chemists explained that the observation is known as "pH buffering", and is a phenomenon by which the solution resists instantaneous pH change.

For the next pH experiment, the 25% NH_4OH solution was diluted with demineralised water at a ratio of 1:6 ($\text{NH}_4\text{OH}:\text{H}_2\text{O}$). The NH_4OH solution was added drop-wise at a low tempo, to ensure that the required pH was not overshoot. The process was tedious, but the pH could be regulated accurately. The volume required to attain this

pH was noted. For the next experimental run, the volume - as noted from the previous addition of NH_4OH - was added to the sample all at once (not drop-wise). The pH showed an irregular pattern of level adjustment, and in the end the same pH was not reached as in the previous experimental run (the pH did not increase enough). A larger volume of NH_4OH solution had to be added to the sample, again at a low tempo, to ensure the required pH was reached. The volumes of the two samples generated differed, and thus it was decided to investigate this pH irregularity phenomenon, albeit only at a theoretical level. The samples were generated from the kerosene batch of experiments and thus the effect this had on the overall reliability of the overall experimental procedure could be minimised.

The samples of the four remaining diluents were experimented with in order to reach a conclusion as to whether (1) the volume of NH_4OH added or (2) the final pH value, would have the biggest effect on the end results.

Experimental procedure 2's experiments were all conducted in the exact same manner, with the addition of NH_4OH set to approximately one droplet per second, until a pH of 4.5 was reached. The procedure thereafter was to add one drop at a time and give the buffering pH time to reach equilibrium, so that it could be determined if another drop of NH_4OH was required. The pH for all the samples that followed had similar values and the volume of NH_4OH added to each sample corresponded closely. This method of NH_4OH addition was considered to be more accurate than the method used during experimental procedure 1's experiments.

A theoretical explanation for the phenomena noticed and described in this section will be explained below in more detail.

3.9.1 Buffering

A buffer solution is an aqueous one consisting of a mixture of a weak acid and its conjugate base, or a weak base and its conjugate acid. In this instance, the buffer solution is the ammonium sulfate solution, which is the aqueous stripping solution (the solution that has to strip the uranium from the solvent) in the combined stripping phase. The buffer solution has the property that the pH of the solution changes little when a small amount of acid or base is added to it. Buffer solutions are used to keep the pH at a nearly constant value in a wide variety of chemical applications. Thus some of the added reagent (NH_4OH) is consumed in shifting the equilibrium in accordance with Le Châtelier's principle, and the pH changes by less than it would if

the solution were not buffered. In general, the pH of a buffer solution can be easily calculated (if the composition of the solution is known) by means of an *Initial, Change, Equilibrium* (ICE) table. One should remember that the calculated pH may differ from measured pH.

3.9.1.1 Definition of buffer capacity

Buffer capacity is a quantitative measure of the resistance of a buffer solution to pH change on addition of hydroxide ions. For an aqueous solution, the buffer capacity is defined in terms of the concentration of acid or base that must be added to influence pH. The formal definition of the buffer capacity is given by the equation:

$$\beta = d C_b / d(\text{pH}) = -d C_a / d(\text{pH})$$

where C_b represents the concentration of the added base and C_a represents the concentration of the added acid.

Buffer capacity is always positive and every solution resists pH change according to Le Châtelier's principle. Because pH goes down upon the addition of acid, a subtraction sign is required when considering acid. Buffer capacity is a continuous and non-linear function - therefore it is a derivative. The buffer capacity can be resolved into a series of terms, with one term for each active component.

$$\beta = \beta_{\text{OH}^-} + \beta_{\text{H}^+} \sum \beta_{i^*}$$

(all of which are weak acids and bases)

For convenience, the first two terms ($\beta_{\text{OH}^-} + \beta_{\text{H}^+}$) are often combined and referred to as the buffer capacity of water, β_w . However, β_{OH^-} and β_{H^+} increase upon the respective addition of strong Arrhenius bases and acids (Urbansky and Schock, 2000).

3.9.1.2 Computation and numerical approximation

For this investigation, the calculation of the buffer capacity is not necessary, but it is important to note this phenomenon, so that a clearer understanding of the pH changes of the solution can be attained.

Computing the buffer capacity equations can be accomplished with a commercial spreadsheet. Extremely complicated cases may be approximated with reasonable

accuracy. Equilibrium constants generally have at least a 1–5% uncertainty. Accordingly, even the analytic solutions are limited by experimental error.

3.9.1.3 Applications

Buffer capacity is a guide to titration. Plots of buffer capacity can be used to find regions of maximal buffering when a mixture of species is present, and to estimate the overall amount of acid or base that may be added without changing solution pH. Such a need is common in aqueous studies and can be encountered in many disciplines (Urbansky and Schock, 2000).

3.10 Methodology: Experimental procedure 4

The optimum result for experimental procedure 1 and experimental procedure 2's experiments were combined and a solution was prepared according to the optimal composition:

- Third-phase inhibitor: 2 vol.% isodecanol
- Extractant: 5 vol.% Alamine 336
- Diluent: 93 vol.% SSX 210

The sample was precipitated in the experimental setup of the precipitation section of the South Uranium Plant, and a sample was obtained from the plant to compare with it.

2 L of the OK Liquor was prepared using the experimental procedure 1's process steps. The OK Liquor was then placed in a glass vessel (batch process) with the following input parameters:

Precipitation input parameters	
Temperature	42°C
Stirrer	120 rev/min
Ammonia flow rate	5 L/h
Ammonia purity	99%
Air flow rate	1.5 L/h

The ADU that precipitated out was filtered onto Whatman 40 filtration paper using a Buchner funnel and flask. The filtration paper containing the ADU was dried in an oven at $\pm 100^{\circ}\text{C}$.

The sample was analysed at the scanning electron microscope (SEM) analysis laboratory at the North-West University, Potchefstroom. Micrographs and sample compositions were obtained that could be compared to samples prepared from OK Liquor sourced from the South Uranium Plant under the same conditions.

3.11 Analysis

Except for the SEM analysis conducted at the North-West University, analysis was carried out by personnel from the AngloGold Ashanti Vaal River Laboratories. This ensured that a standard method for analysing samples was used. Table 3-2 specifies the analysis method and compounds analysed.

Table 3-2: List of analysis methods and samples

Analysis	Sample quantity	Method used
Uranium Aqueous (U_3O_8 equivalents)	10 ml	ICP
Uranium Organics (U_3O_8 equivalents)	10 g	XRF
Sulfates (SO_4)	5 ml	RADICALS
Total Fe	10 ml	ICP

3.11.1 Inductively coupled plasma

The more formal reference to this type of analysis, commonly abbreviated as ICP, is "*Inductively coupled plasma atomic emission spectroscopy*" (ICP-AES) (see Sigel & Sigel, 1994). This is an analytical technique used for the detection of metals. It is a type of emission spectroscopy that uses the inductively coupled plasma to produce excited atoms and ions that emit electromagnetic radiation at wavelengths characteristic of a particular element. The intensity of this emission is indicative of the concentration of the element within the sample. In this instance, ICP was used to analyse for U_3O_8 equivalents, and the total Fe content in the aqueous samples that was produced in all three steps of the procedure.

3.11.2 X-ray fluorescence

Beckhoff et al. (2006) have discussed the physics and operation of X-ray fluorescence (XRF). This is a reliable, multi-elemental and non-destructive analytical method specifically used for elemental analysis and chemical analysis and is widely used in research and industrial applications. In this instance, the XRF analysis was used to detect the amount of U_3O_8 equivalents present in the solvent that was generated during the extraction and stripping steps. A sample of 10 grams was used for each analysis.

3.11.3 Sulfate analysis

The analysis was conducted by the AngloGold Ashanti Vaal River Laboratory according to a standard laboratory analysis test method (the gravimetric determination of sulfates in plant solutions). Sulfate is precipitated in a hydrochloric acid medium (pH=2.5) as barium sulfate, by the addition of barium chloride. To ensure all the sulfate, bi-sulfate and sulfate complexes were converted to sulfate ions to partake in this reaction, the solution is left at a moderate heat for two hours after lowering the pH of the sample and adding barium chloride. The precipitation is carried out near the boiling temperature of the solution and after a period of digestion, the precipitate is filtered, washed with hot de-mineralised water, until free of chloride, dried and weighed as barium sulfate (AngloGold Ashanti, 2006).

3.12 Data analysis and calculations

When the data were processed, little focus was placed on actual numerical values of the results obtained from the analysis reports. A comparative analysis was instead conducted between the results of different experiments. This was done by conducting all the experimental procedures under the same conditions and using the same equipment for each experimental run. The experiments were also repeated three times to ensure a reliable result.

For an overview of the results, bar charts of each of the five diluents were plotted for each unit operation (extraction, scrubbing and stripping). The aqueous results are presented separately from the organic phase results. In each instance the uranium-bearing compound (the desired product), SO_4^{2-} (a vital ion needed for the precipitation step) and overall iron content (one of the main product impurities) were analysed and graphs were plotted for ease of reference. Each bar chart represents

the analysis results obtained for a specific compound or element (U_3O_8 , SO_4 or Fe) present in the samples generated from the different experimental procedures. A comparison can be made of the concentration (g/L) of the compound present in the solution, to evaluate comparatively the efficiency of the extraction, scrubbing and stripping for the different diluents and solvent compositions.

4 Results and discussion

4.1 Experimental procedure 1: Diluent selection

4.1.1 General information

A process of elimination was used in evaluating the data generated from experimental procedure 1. This elimination process enables a better understanding of decisions about which diluent to use in experimental procedure 2. It is important to observe the inequities of each diluent and the result this has on the three species (U_3O_8 , SO_4 and Fe) that was monitored during the investigation. The diluents experimented with during this phase of the investigation, were selected primarily with regards to their flash point, as the fire hazard of the diluent that needs to be replaced was the biggest risk to the plant. The diluents that will be investigated are qualified by the properties in table 4-1.

Table 4-1: Summary of important diluent properties

Diluent	Flashpoint	Viscosity	Aromatic content	Density
	(°C)	(cSt) @ 40°C	(vol.%)	(g/cm ³) @ 20°C
Kerosene	42	1.30	10-45	0.79
SSX 150	45	1.19	0.3	0.88
Shellsol D70	77	1.97	0.0	0.79
SSX 210	88	1.90	0.1	0.75
B-100	130	7.10	0.0	0.79

The summer temperatures of the plant rarely exceed 40°C, although surface temperatures of some equipment might exceed this value. A diluent range with a flashpoint higher than 45°C was recommended.

The experimental procedure as described in Chapter 3.7 was carried out and below is a summary of critical overall results, with a short discussion to qualify the decision that had to be taken before proceeding with experimental procedure 2.

4.1.2 Phase separation time

Phase separation time is an important parameter in the practical implementation of a diluent on industrial scale, as the equipment capacity is influenced by the residence

times. During the experimental procedure for each diluent, the phase separation time after each agitation procedure was noted to compare with the separation time of the diluent currently used in the plant. These results are represented in table 4-2.

Table 4-2: Phase separation duration times

Phase separation times (s)					
	Kerosene	SSX 150	SSX 210	B-100	Shellsol D70
Extraction	50	80	70	1380	Stable emulsion
Scrubbing	30	65	55	2100	Stable emulsion
Stripping	20	50	40	3600	Stable emulsion

A graphic presentation of the data is given in figure 4-1, excluding the data concerning Shellsol D70 and B-100 (Biodiesel) due to the stable emulsion that formed during the agitation process and the comparatively long phase separation time respectively.

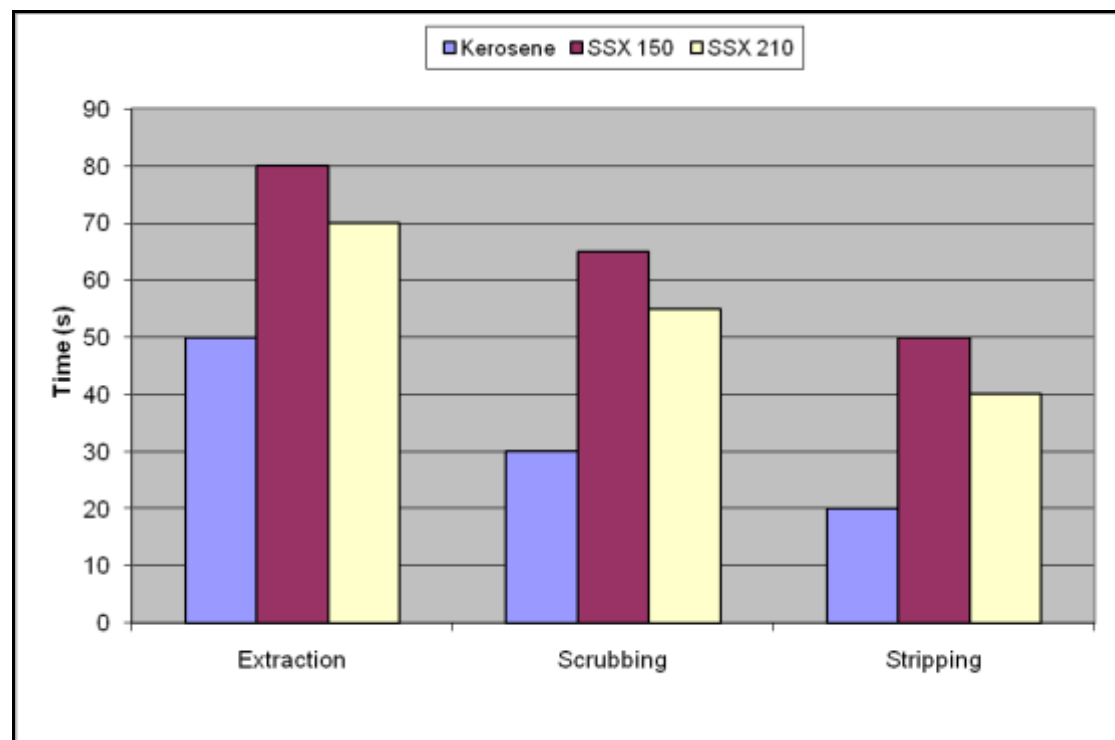


Figure 4-1: Phase separation times for experimental procedure 1

Kerosene (see figure 4-1) has the shortest (best) phase separation times, followed by SSX 210 with noticeably longer separation times. The reason for the difference in separation times is because of the polar/nonpolar and hydrophobic/hydrophilic nature of the diluents, as well as the interfacial tension relative to the aqueous phase (Louw,

2009). The drawback of using a diluent with a high aromatic content, is the accompanying carcinogenic health risks and the increased volatility due to a lower flashpoint.

The Bio-diesel B-100 has an unrealistically high settling time when considering the up-scaling of equipment to accommodate such long residence times.

In the case of the Shellsol D70 experiment, an emulsion formed that appeared to be an entrapment phase, and some aqueous eluate became captured in organic films (bubbles). A long settling time was permitted, but no further phase separation occurred. It was considered that a “new” third phase had not formed, but rather that there was an entrapment problem, which would not allow the phases to separate in a reasonable time. Shellsol D70 only underwent the extraction contact procedure, but was disqualified from further experimental test work because of the entrapment observation. The emulsion was formed because the aromatic content of the Shellsol D70 is less than 100 mg/kg.

After each agitation procedure, when the agitated solution was left still for phase separation to occur, no third phase formed. It should however be considered that under less ideal circumstances (such as an industrial plant application); a third phase would most likely be present, due to the M-organic complex's insolubility in the organic phase. In such an instance, the uncomplexed organic phase is separated from the aqueous phase by the presence of a U-complex organic layer.

The three species (U_3O_8 , SO_4 and Fe) with the most pronounced influence on the efficiency rating of the SX process and the delivery of an OK Liquor with favourable composition to the precipitation section of the plant are evaluated and discussed below. These results form part of the evaluation of the effectiveness of the SX section regarding the specific composition of the desired product (ADU), the purification of the eluate of certain detrimental elements (Fe), and the formation of compounds (SO_4) for the precipitation of ADU. The eluate received from the plant was analysed and found to have the composition shown in table 4-3.

Table 4-3: Eluate composition

Eluate content (g/L)			
	U₃O₈	SO₄	Total Fe
Eluate (standing)	2.56	100.30	0.796
Eluate (mixed)	3.02	68.89	0.896
Eluate (mixed)	3.04	67.96	0.902

Notice was taken of the settling effect of the particles suspended in the aqueous acidic medium (the eluate), and care was taken to agitate the sample source before decanting over to smaller samples. The average U₃O₈ value according to the South Uranium Plant is 3-5 g/L, depending on the quality of the ore being processed.

4.1.3 Diluent effect on U₃O₈ concentration

The focus of the overall process is the production of ADU. Thus the different solutions (raffinate, loaded organic, scrub water, OK Liquor and stripped organic) produced during experimental procedure 1 were evaluated to consider what happens to the U₃O₈ in both the aqueous and solvents. The bar chart in figure 4-2 depicts a comparative summary of the results of the U₃O₈ analysis, which were obtained after completion of the procedure mentioned in Chapter 3.7. The y-axis indicates the concentration (g/L) of the species under investigation, and the x-axis refers to the organic and aqueous solutions formed after each agitation procedure, when the species were transferred into or from the organic or aqueous phase. Each diluent's bar is indicated by the corresponding colour from the legend blocks.

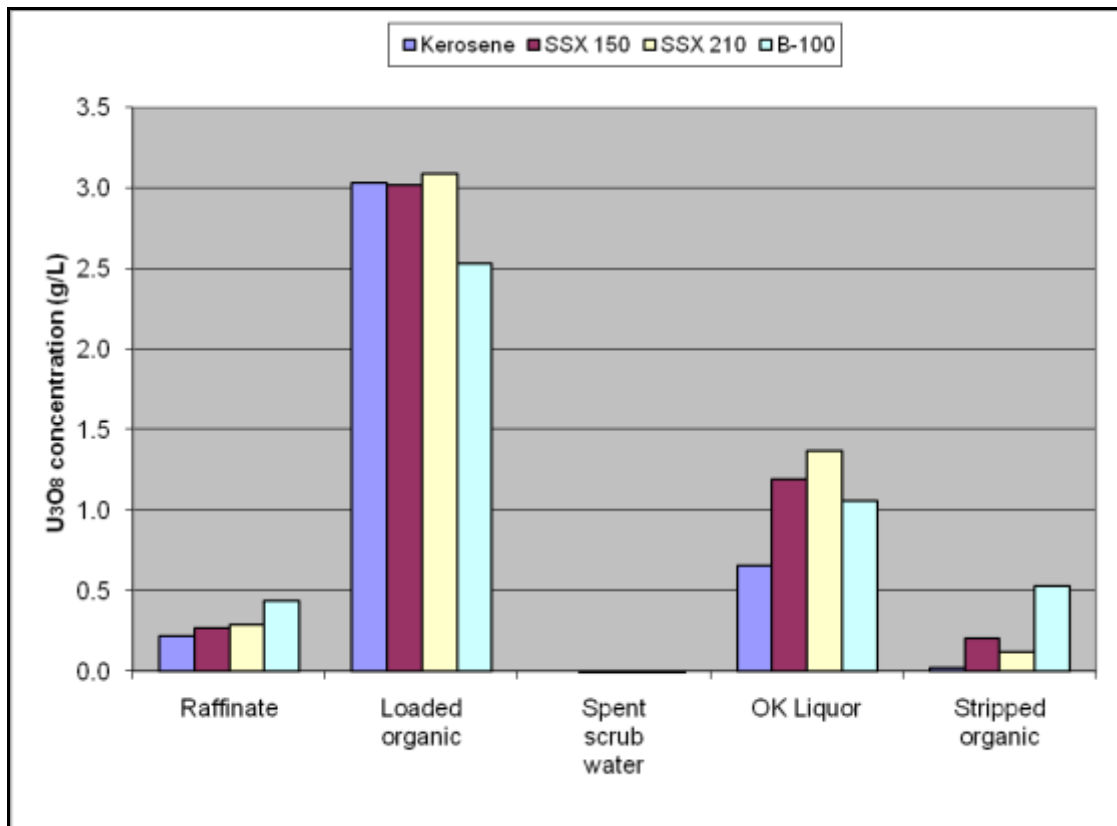


Figure 4-2: Comparison of U_3O_8 analysis for experimental procedure 1

Figure 4-2 shows five groups of bars, which correspond to the respective numbering for the paragraphs that follow. This notation is used throughout this chapter of the report.

1. To interpret the graph, it should be noted that for the first group of bars (raffinate) the U_3O_8 concentration should be as low as possible to indicate high extraction efficiency from the eluate into the solvent. Kerosene performed the best here, followed closely by the SSX range.
2. For the second group (loaded organic), the U_3O_8 concentration should be as high as possible to indicate that the organic phase was loaded efficiently. In this reaction step, it can be noted that SSX 210 contained the highest concentration of uranium sulfate complexes (refer to Chapter 2.3.4.1).
3. In the third group (spent scrub water), none of the valuable product was lost due to the scrubbing of impurities.

4. In the fourth group (OK Liquor), the effectiveness of the U_3O_8 stripping to the aqueous ammonium sulfate solution was evaluated. A higher value is again an indication of a better stripping efficiency. Here the SSX 210 performed most effectively.
5. Group five (stripped organic) indicated how well the U_3O_8 was transferred out of the organic phase into the aqueous phase, and how much of the U_3O_8 will be recycled back upstream in the process. The kerosene samples had the lowest residual U_3O_8 content after stripping.

From figure 4-2 and the discussion above, it can be concluded that kerosene, SSX 150 and SSX 210 behave similarly and, when compared to the D70 (which was eliminated due to unacceptable phase separation time), all three are seemingly viable options.

It is now again worth mentioning that the results are evaluated by qualitative assessment and not by quantitative results. A simple comparison of the bars on the graph between involved diluents and the results they produce will lead to a conclusion about which diluent to investigate further. A mass balance would have quantified the results, but since the density and volume for each of the solutions was not precisely recorded, a mass balance could not be compiled.

4.1.4 Diluent effect on SO_4 concentration

U_3O_8 is precipitated as ADU, which is a sulfate complex, making the availability of sulfate ions for compound formation a crucial influencing factor. From the chemical reaction equations in Chapter 2.3.4, it is clear that sulfates are indispensable in the formation of the required sulfate complexes that make up each reaction with uranium until ADU can be precipitated. It is also vital to mention that sulfur is one of the main penalising impurities present in the final product (yellowcake) sold by the South Uranium Plant, and the sulfate (elemental sulfur) balance is therefore closely monitored. As in point 4 of the previous section, the absence of sulfate ions leads to insufficient loading of uranium into the OK Liquor solution of the stripping stage. The sulfur content of the various process streams is shown in figure 4-3.

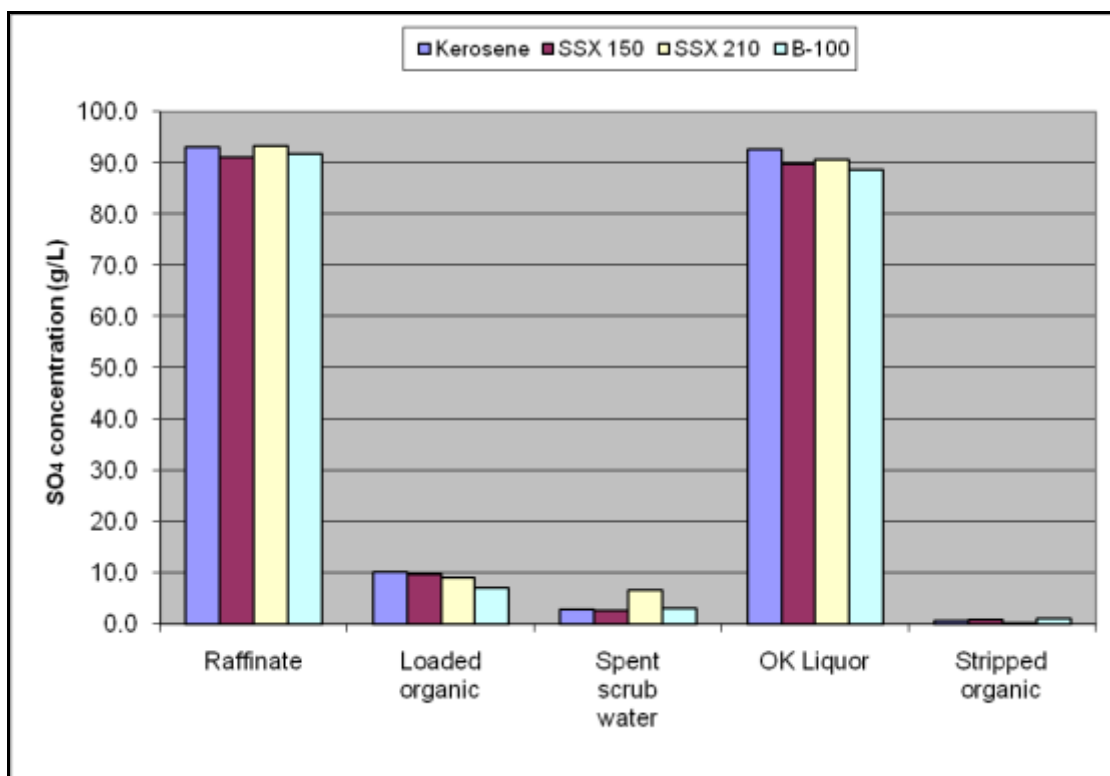


Figure 4-3: Comparison of SO_4 analysis for experimental procedure 1

1. For the first group of bars (raffinate) the SO_4 concentration (g/L) is already high. This is as a result of the sulfuric acid lixiviant used in the leaching section. The presence of a high SO_4 concentration indicates that there was a transfer of the $\text{UO}_2(\text{SO}_4)_2^{2-}$ ions to the amine ions $((\text{R}_3\text{NH})_2\text{SO}_4)$, leaving excess SO_4^{2-} ions in the raffinate (refer to chemical reactions in chapter 2.3.4).
2. For the second group (loaded organic), there is little free SO_4 left in solution, as most of these ions have already formed a uranium complex. The SO_4 ions that are still present are expected to come from the entrapment of ions during the vigorous agitation procedure. Alternatively there could have been extraction of HSO_4^- by amine. When referring to figures 4-1 and 4-2, an interchangeable behaviour between the two species (U_3O_8 and SO_4) can be observed. In this specific experimental procedure step, it can be noted that SSX 210 formed the most uranium sulfate complexes, and that it had a low amount of unbound sulfate ions left in solution. This indicated effective complex formation.
3. In the third group (spent scrub water) it can be seen that the SSX 210 gave off the highest amount of sulfates to the scrub water. This is a positive effect, considering it is present via entrainment.
4. In the fourth group (OK Liquor), the presence of a high sulfate concentration is due to the nature of the aqueous solution. As explained in the previous section,

the sulfate concentration for this step in the experimental procedure should have been more than 120 g/L to obtain complete uranium stripping.

5. Group five (stripped organic) indicated how well the SO_4 was retained in the process cycle. Little of the sulfate ions remained in the barren solvent, indicating an effective overall transfer of the desired uranium complex to the now loaded OK Liquor, assuming all the sulfate is present as uranium complex.

4.1.5 Diluent effect on Fe concentration

The total Fe content (a combination of ferric and ferrous ions) could only be analysed for in the aqueous solutions. The results are shown in figure 4-4.

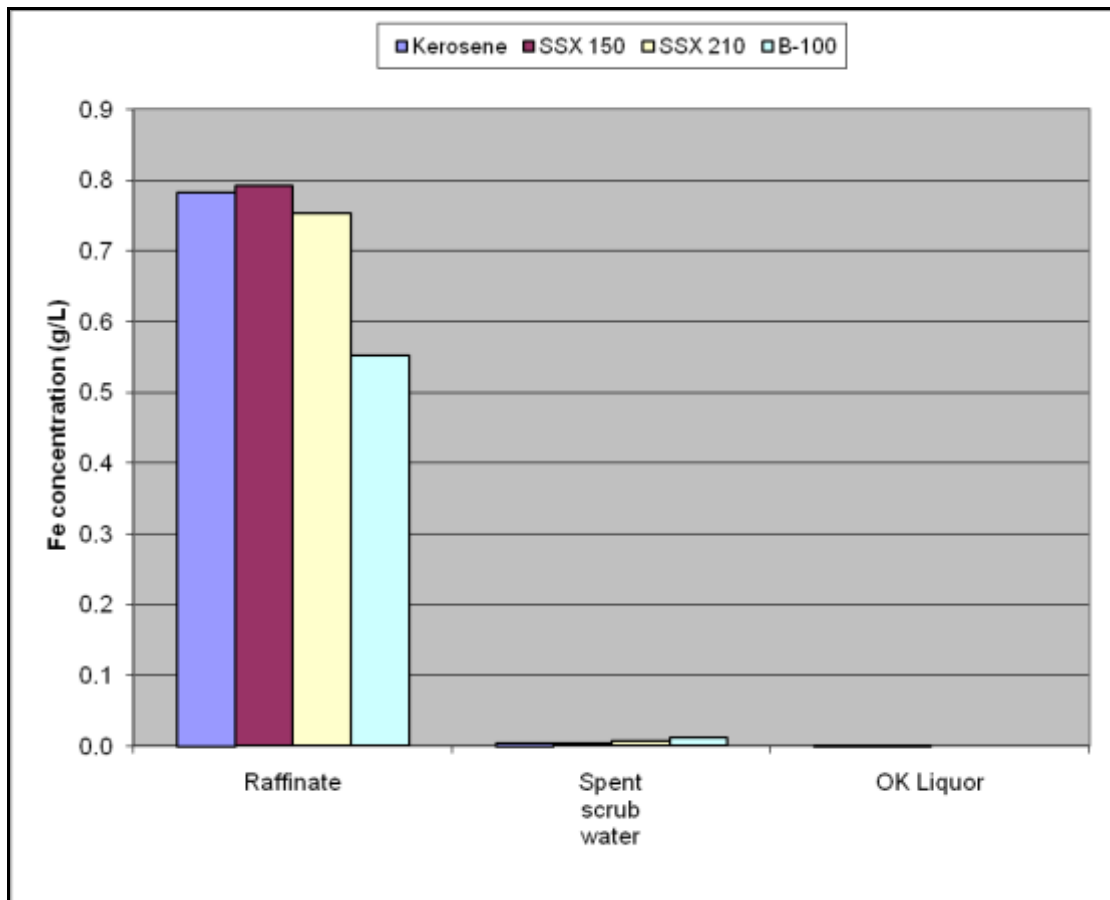


Figure 4-4: Comparison of Fe analysis for experimental procedure 1

1. The total Fe concentration is highest for the first group (raffinate). When considering this with table 4-3, it becomes clear that most of the Fe remains in the extracted eluate. This extraction of iron(III) is a result of the formation of $\text{Fe}(\text{SO}_4)^+$. Small quantities of the Fe will transfer to the organic phase. This is due to some solvation of $\text{Fe}_2(\text{SO}_4)_3$ by the isodecanol.

2. In the third group (spent scrub water) only trace amounts of Fe were removed in the scrub water for all four solvents.
3. Group five (stripped organic) indicated how little Fe was present in the product of the SX section (the OK Liquor) and the data generated by the laboratory analysis showed that the Fe content in most cases was less than 2 mg/L (<0.002 g/L).

Figures 4-2 to 4-4 summarise the thirteen individual graphs generated by experimental procedure 1. The individual graphs show (and were evaluated in) more detail and can be found in Appendix C.

In conclusion, because of the efficient stripping of solvent containing SSX 210, and the effective loading of the aqueous solution contacted with this solvent (in combination with its flash point and phase separation times), SSX 210 was selected as the diluent of choice to conduct experimental procedure 2.

4.2 Experimental procedure 2: Solvent composition

4.2.1 General information

The main goal of experimental procedure 2 was to determine an optimum solvent composition. The volume percentage of extractant (Alamine 336) was varied between 3 and 11 vol.%. According to Mackenzie (1997), the third-phase inhibitor can be kept at 50-60 vol.% of the volume of the Alamine 336 in the composition, depending on some process conditions. 40 vol.% was found to be effective by the South Uranium Plant and was therefore used in these experiments. The volume percentage balance was then filled up to 100% with the diluent (SSX 210) that was selected for use based on the results obtained from the first phase of the experimental procedure. The exact compositions of the five solvents can be seen in table 3-1.

The main influence of varying the amount of Alamine 336 in the solvent can be predicted using the chemical reaction shown in section 2.3.4.1 (Reaction 7). Alamine 336 is the tertiary amine, represented by three R-groups (R represents any alkyl chain) attached to an N-group ($(R_3NH)_2SO_4$), in the chemical equation to which the entire uranium sulfate complex binds during the extraction step. The tertiary amine needs to be protonated first to convert it to an anion exchanger. Uranium is present in the acidic sulfate leach liquor as the divalent ($UO_2(SO_4)_3^{2-}$) or tetravalent

($\text{UO}_2(\text{SO}_4)_3^{4-}$) uranyl sulfate species. It is this species that is then extracted by an anion-exchange reaction.

The main factor influencing the decision regarding which volume percentage composition to use will be deduced from the effect that the newly chosen diluent (SSX 210) has on the U_3O_8 cycle of extraction, scrubbing and stripping. The effect the different compositions have on the sulfates and total iron concentrations are only looked at briefly, with some explanation offered where a trend is observed.

4.2.2 Phase separation time

Differences in the liquid-liquid phase separation time play a major role in the design of a plant, as described in the previous section. The separation times for the different solvent compositions are given in table 4-4.

Table 4-4: Liquid phase separation duration times

Phase separation time (s)			
	Extraction	Scrubbing	Stripping
3 vol.% Alamine 336	77	65	45
5 vol.% Alamine 336	69	57	43
7 vol.% Alamine 336	103	89	55
9 vol.% Alamine 336	110	120	76
11 vol.% Alamine 336	183	560	116

The data were plotted on a graph to identify the composition with the shortest (and most effective) phase separation time (see figure 4-5).

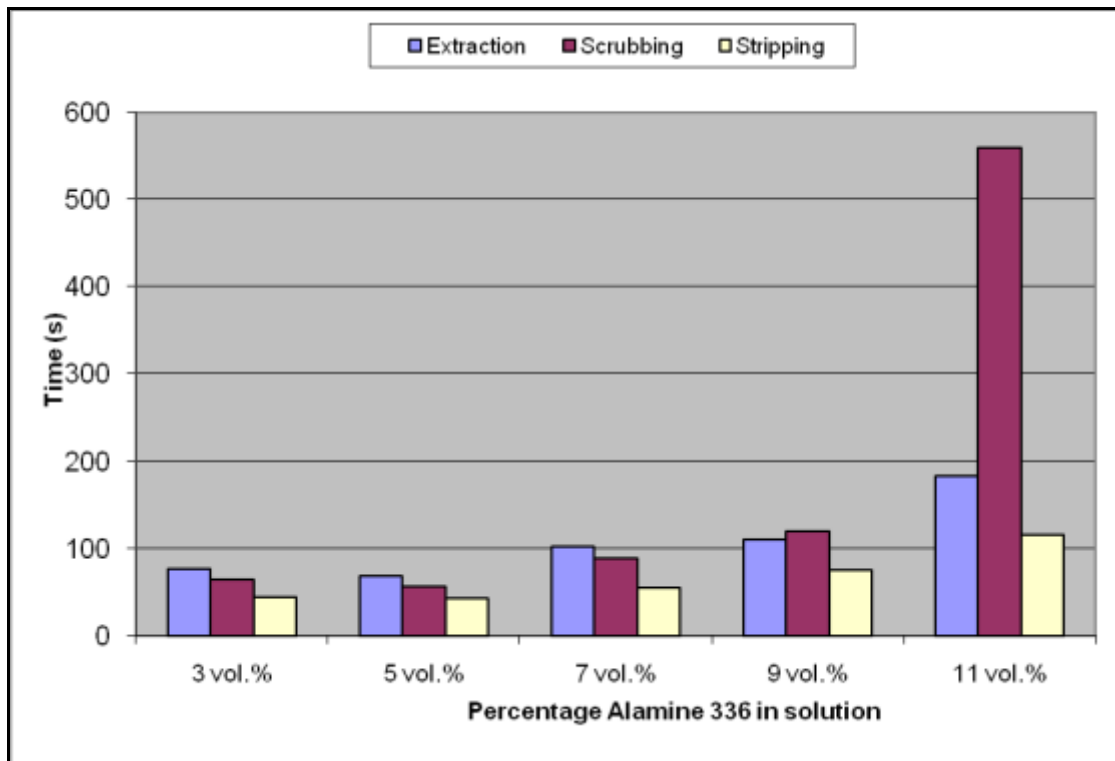


Figure 4-5: Phase separation times for experimental procedure 2

From figure 4-5, the 5 vol.% Alamine 336 with 2 vol.% Isodecanol and 93 vol.% SSX 210 was identified as the composition with the best phase separation time. This is the composition currently used by the South Uranium Plant. The composition will also have an effect on the efficiency with which the three main species (U_3O_8 , SO_4 and Fe) were extracted, scrubbed and loaded. The following sections concern those analysis results.

4.2.3 Composition effect on U_3O_8 concentration

Figure 4-6 illustrates the effect that different compositions of the organic phase will have on the extraction of uranium.

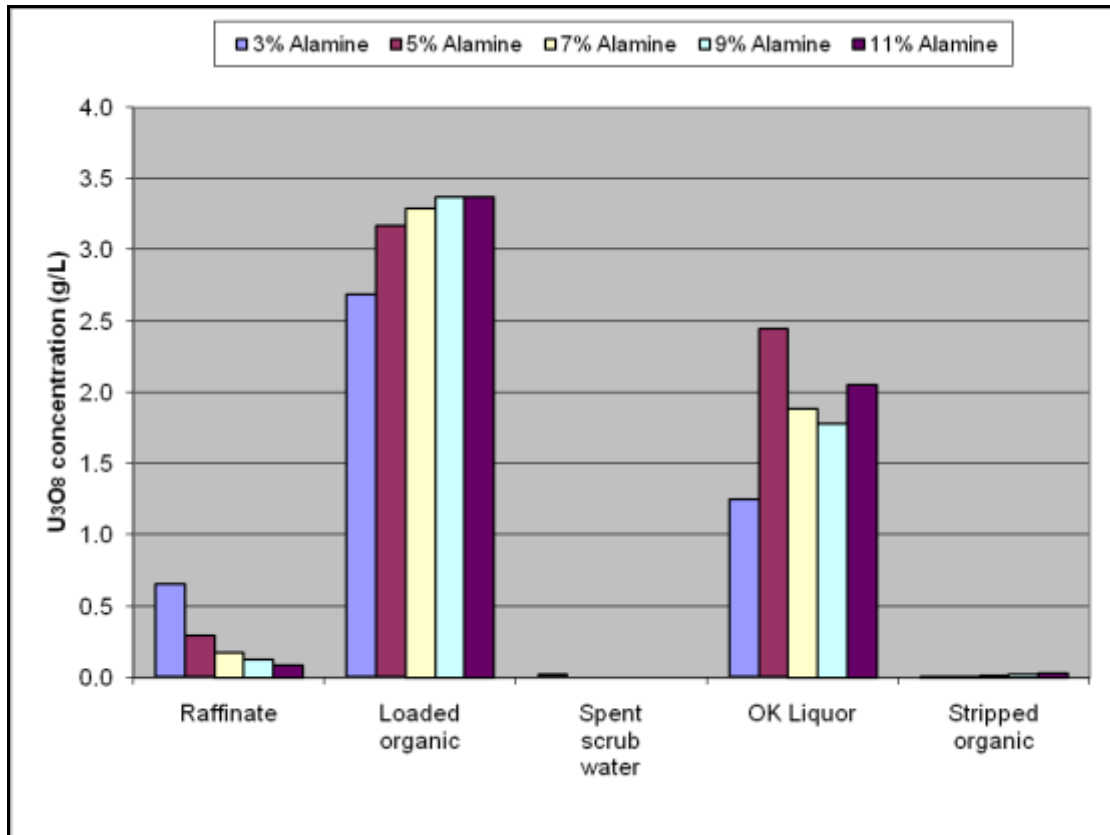


Figure 4-6: The effect of solvent composition on U_3O_8 analysis

1. The first group (raffinate) shows that the eluate contacted with a solvent containing a higher volume percentage Alamine 336 extracted more U_3O_8 .
2. The second group (loaded organic) shows that although there is not a large deviation in the U_3O_8 concentration between the five different compositions, the U_3O_8 is loaded more efficiently onto the organic phase with a higher Alamine 336 content.
3. In the third group (spent scrub water) the only loss of U_3O_8 was in the 3 vol.% Alamine 336 solvent. It can thus be deduced that there was not enough Alamine 336 in the solution to form a complex with the leached uranium in the eluate (see reaction chemistry in section 2.3.4). Scrubbing removes the physically entrained aqueous phase, so this indicates that either the phase separation was incomplete or there was entrainment of eluate in the organic phase.

4. For the fourth group (OK Liquor) 5 vol.% composition showed the most favourable loading characteristics. (The 11 vol.%'s high result is possibly caused by an extreme outlier, because the value generated by the analysis does not correlate with the predicted theoretical result.)
5. In the final group (stripped organic) negligible U_3O_8 remained in the organic phase for all the compositions, but the 11 vol.% retained the most U_3O_8 . It can therefore be accepted that the varying composition does not have such a large influence on the stripping characteristic in the organic phase.

4.2.4 Composition effect on SO_4 concentration

Because the uranium is extracted by the mechanism of binding with sulfate complexes, it is extremely important that the sulfate content is monitored in all the solutions. In this section the solvent composition effects on the SO_4 are illustrated in figure 4-7.

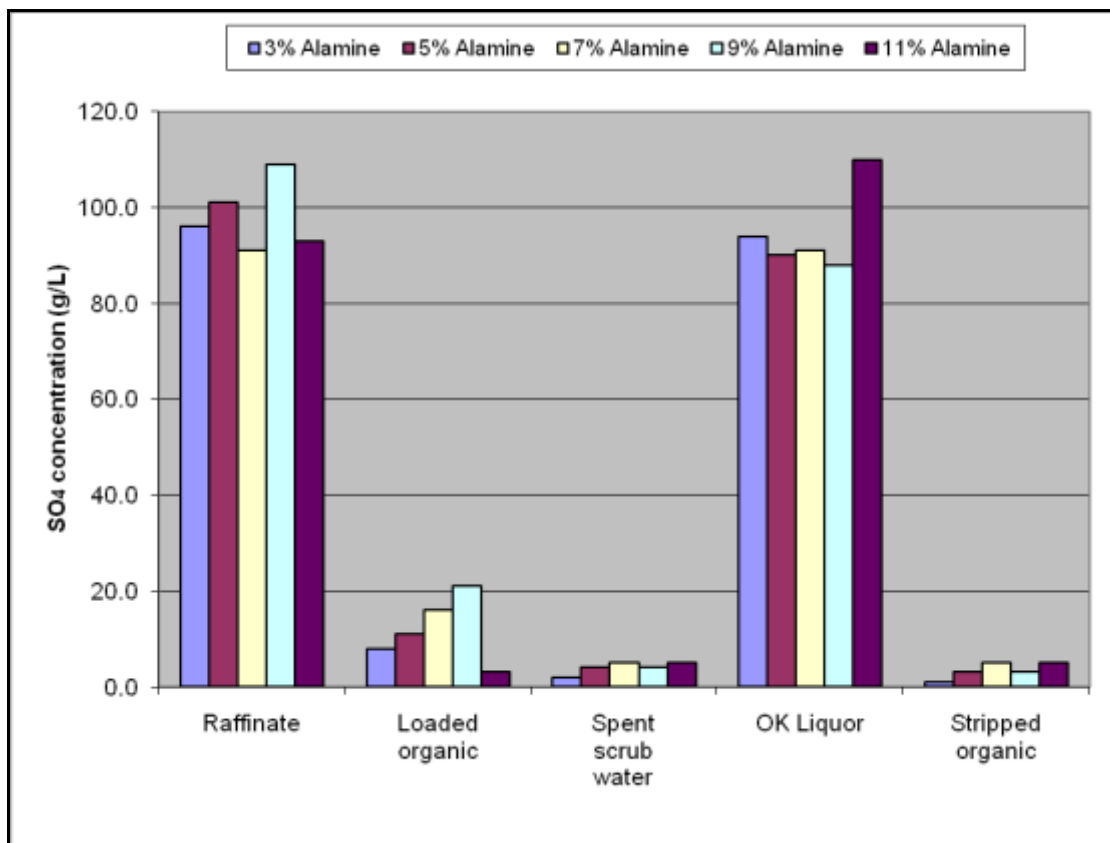


Figure 4-7: Solvent composition's effects on SO_4 analysis

1. For the first group (raffinate) the SO_4 concentration is already high. This is as a result of the sulfuric acid lixiviant used in the leaching section. The presence of a

high SO_4 concentration indicates that there was a transfer of the $\text{UO}_2(\text{SO}_4)_2^{2-}$ ions to the amine ions, leaving excess SO_4^{2-} ions in the raffinate.

2. For the second group (loaded organic), there is little free SO_4 left in solution, as most of these ions are already formed a uranium complex. The SO_4 ions still present are expected to come from the physical entrapment of the aqueous phase during the vigorous agitation procedure. When referring to figures 4-1 and 4-2, an interchangeable behaviour between the two species (U_3O_8 and SO_4) can be observed.
3. In the third group (spent scrub water) it can be seen that the lower Alamine 336 compositions lost the least amount of sulfates to the scrub water. Alamine 336 is selective for extraction of uranium complex over the extraction of sulfate and bisulfate anions. When limited capacity is available (i.e. as extractant concentration is lowered), less sulfate and bisulfate anions will be extracted and so less will show up in the spent scrub liquor. The spent scrub liquor will therefore also be less acidic.
4. In the fourth group (OK Liquor) the presence of a high sulfate concentration is again due to the nature of the composition of the aqueous solution (which is ammonium sulfate dissolved in demineralised water). Again the 11 vol.% Alamine 336 composition displays an unexpected result which cannot be explained.
5. Group five (stripped organic) indicates how well the SO_4 was retained in the aqueous solution of the process cycle. Few of the sulfate ions remained in the barren solvent after the agitation step. This indicates an effective overall transfer of the desired uranium sulfate product complex and also good stripping of SO_4^{2-} and HSO_4^- .

4.2.5 Composition effect on Fe concentration

As mentioned previously, iron content is a major cause of penalties on the quality of the final product. Figure 4-8 clearly illustrates the iron content transfer to and from the different solutions.

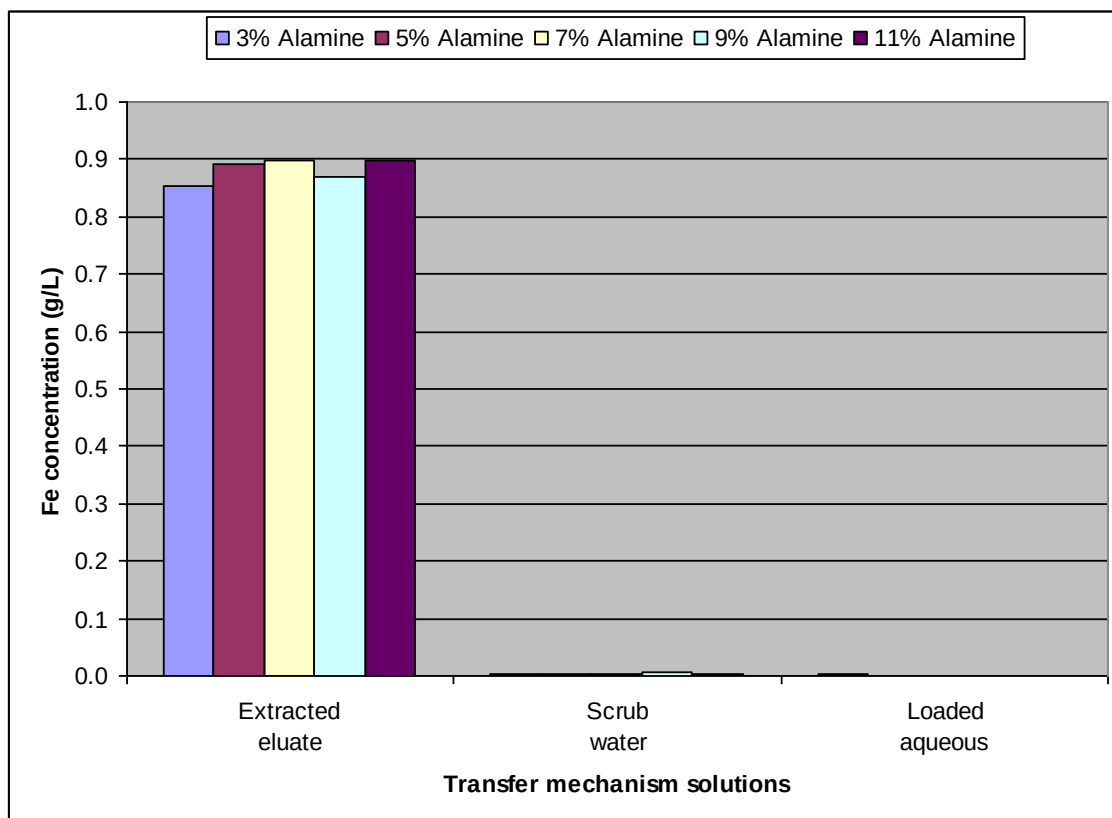


Figure 4-8: Solvent composition's effects on Fe analysis

The interpretation of figure 4-8 is the same as figure 4-4. Therefore, to avoid unnecessary repetition, the reader is referred to section 4.1.5 (Organic carrier effect on Fe concentration), for a detailed explanation of these results.

4.3 Experimental procedure 3: pH investigation

4.3.1 Diluent selection pH observations

This procedure entailed selecting an diluent with the best SHE characteristics and with high product efficiency. In the procedure the results of the samples generated during experimental procedure 1's stripping procedure, are evaluated and discussed. The stripping process at the South Uranium Plant is a delicate process step, as the effect of the pH causes dramatic alterations in the product OK Liquor delivered to the precipitation section.

4.3.1.1 Kerosene pH results

During the final phase of experimental procedure 1, when the stripping phase was initiated and the pH had to be increased for the uranium sulfate complex to transfer from the organic to the aqueous phase, the addition of NH_4OH to the first sample did

not seem to have a noticeable effect on the pH of the sample after the first few drops were added. The pH also tended to recede back to a lower value when the addition of NH_4OH was paused. Thus, the NH_4OH was added at a higher rate until the required pH was reached. When the addition of NH_4OH was stopped (at the desired pH) the pH did not remain at the level attained and kept increasing in larger intervals until the uranium in the sample eventually precipitated as ADU. The sample was discarded. For the next two samples of the Kerosene batch, care was taken to add the NH_4OH slowly in order to establish a trend in the behaviour of the pH adjustment. Regrettably the volumes of the NH_4OH added to each sample were not noted, but for the subsequent diluents these values were tabulated.

The following figures show the pH reached (after adding a specific volume of NH_4OH to the sample) on the x-axis and the y-axis denotes the concentration of the analysed species. The goal of this graph is to show the pH influence on the concentration of uranium in the two liquid phases indicated by the legend. Only the graphs generated while investigating uranium analysis are shown in this section, as the most important influence is on the uranium species. The graphs showing the effect on SO_4 are shown in Appendix F.

In figure 4-9 it can be seen that the ADU precipitated at the higher pH value (pH = 6.2), resulting in less uranium being present in the aqueous solution. It was recommended that the pH be increased to a value between 5 and 5.5. For a value larger than 5.5, precipitation appeared to set in instantaneously. In both samples there are still trace amounts of uranium sulfate in the solvent.

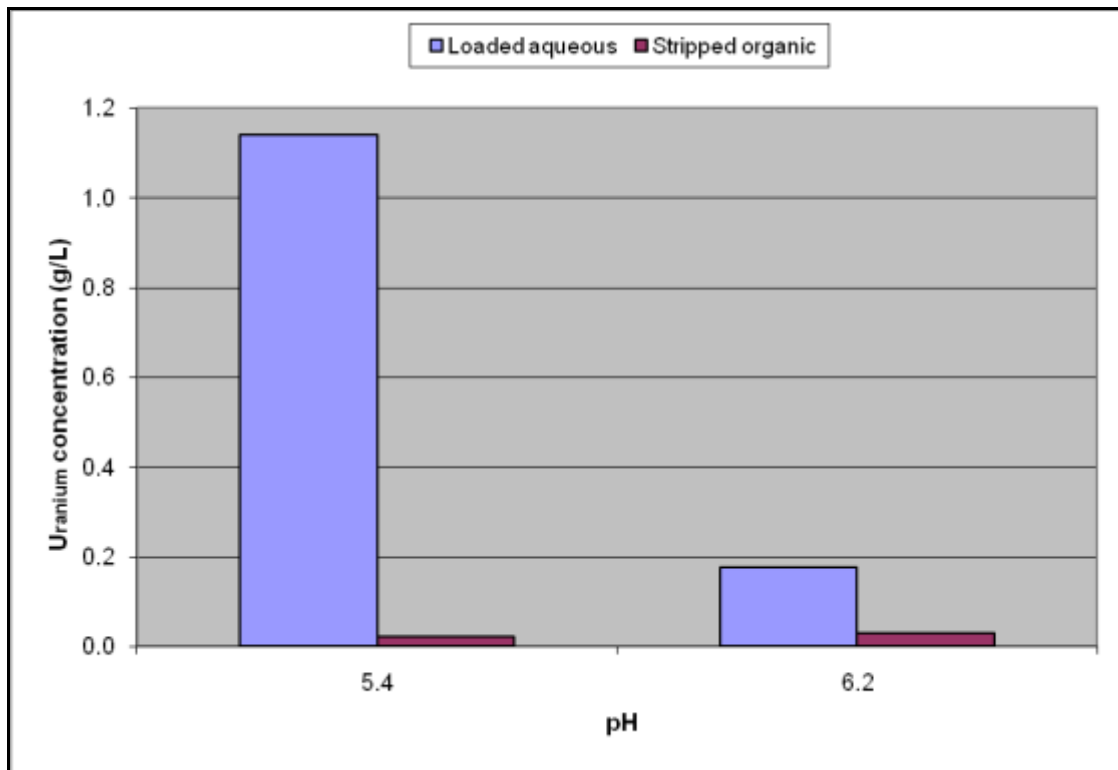


Figure 4-9: pH effect on the Kerosene solvent

4.3.1.2 SSX 150 pH results

Figure 4-10 shows how the pH change in the OK Liquor generated with SSX 150, affected the uranium content in the solution.

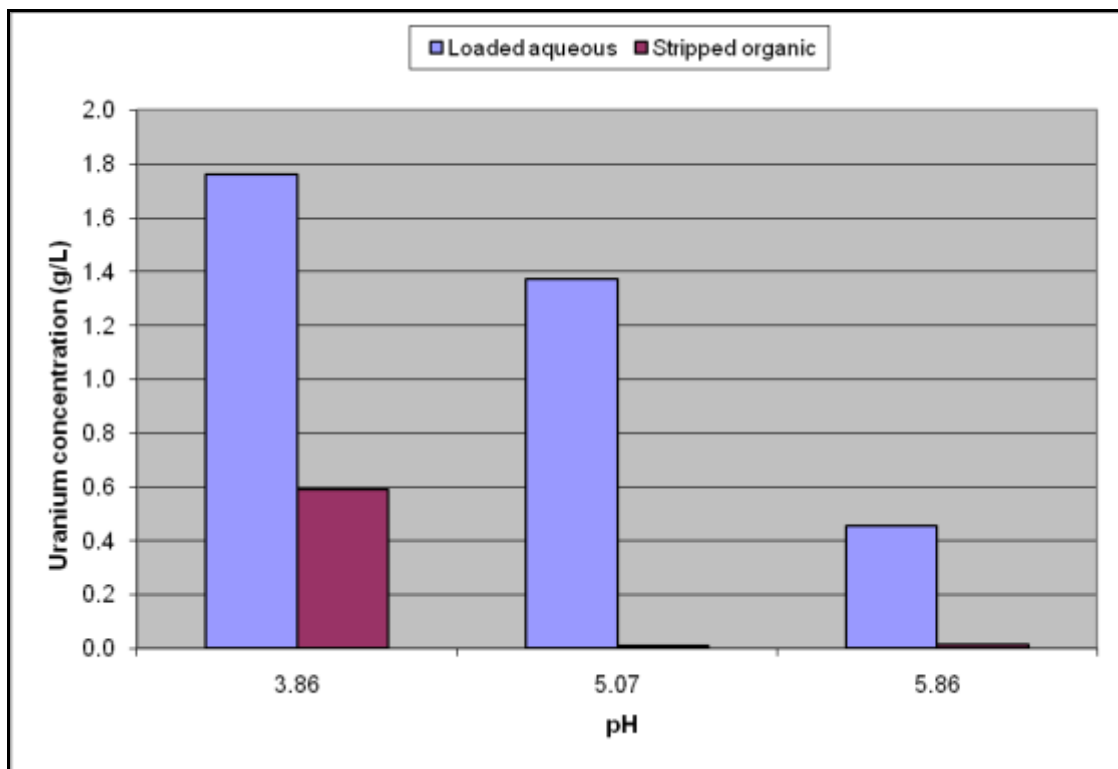


Figure 4-10: pH effect on the SSX 150 solvent

For all three samples, the volume of NH_4OH added to the sample was kept constant, but the tempo of addition was varied, and the dramatic effect on the pH of the addition tempo (see table 4-5) can clearly be seen.

Table 4-5: SSX 150 stripping characteristics

pH	Volume	Tempo
3.86	6.8 mL	Fast
5.07	6.8 mL	Moderate
5.86	6.8 mL	Slow

In figure 4-10 it appears that a pH of 5.07 was already too high, since a lower pH caused less precipitation and thus more of the required product could be transferred to the aqueous OK Liquor passed on to the next process step. A pH of 3.86, however, permits too much of the desired product to remain in the solvent. The third sample is again evidence of the negative effect that a pH in excess of 5 has on the desired product. A clear correlation with the buffering phenomena can be identified (table 4-5), as the pH rises much higher for the slow addition of NH_4OH than with a fast addition. Since pH control is such a sensitive process parameter, meticulous selection of process equipment must be conducted for the plant upgrade, but this will be discussed in more detail in the following chapter.

4.3.1.3 SSX 210 pH results

Figure 4-11 shows the result the pH change in the OK Liquor generated with SSX 210, had on the uranium content in the solution, while table 4-6 shows the volume and tempo of addition of NH_4OH .

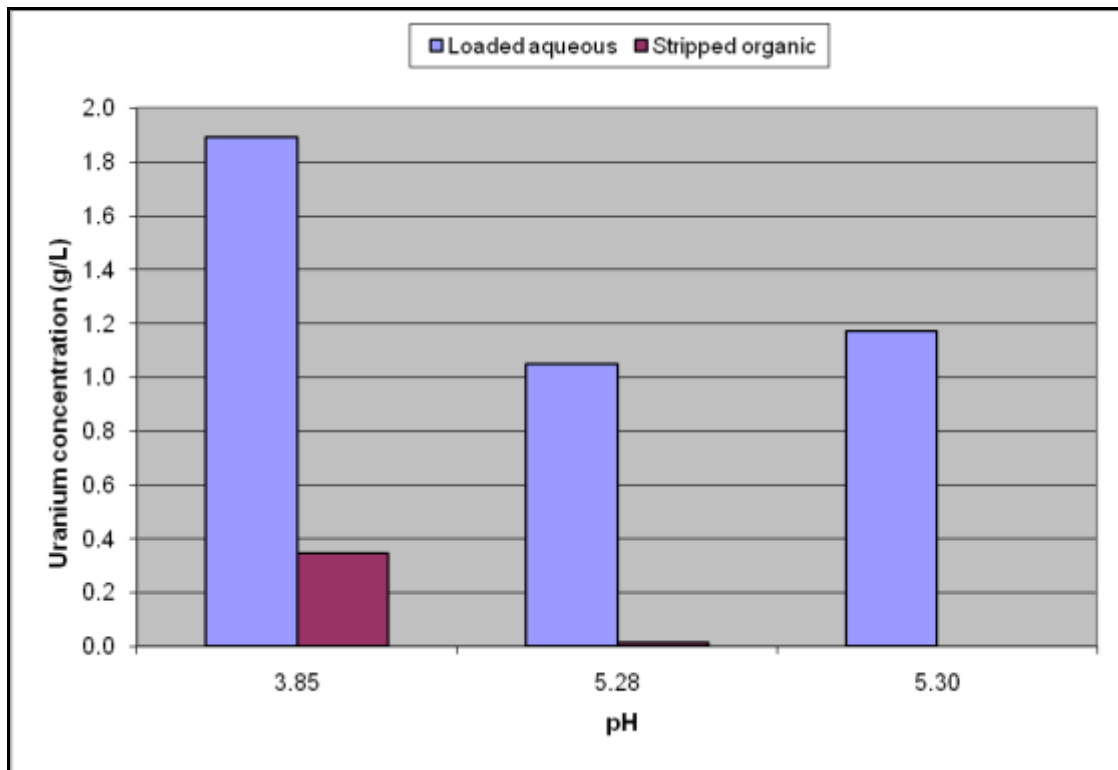


Figure 4-11: pH effect on the SSX 210 solvent

The stripping results of the SSX 210 are similar to those of SSX 150. Note, however, that the sample with a pH of 5.3 contained a higher concentration of uranium in the aqueous and less in the solvent, than for a lower “recommended” pH of 5.28. The pH difference is small, but the effect is believed to have a direct correlation with the tempo of NH_4OH addition.

Table 4-6: SSX 210 stripping characteristics

pH	Volume	Tempo
3.85	6.8 mL	Fast
5.28	5.8 mL	Slow
5.30	6.8 mL	Moderate

From table 4-6 it seems that the tempo of addition has a substantial effect on the terminal pH, and the pH has a substantial effect on the amount of uranium stripped to the aqueous phase. Consideration of the Biodiesel results will confirm this conclusion.

4.3.1.4 Biodiesel pH results

Figure 4-12 shows that a pH with a higher value causes too much of the desired ADU product in the aqueous phase to precipitate out, and to deposit on the walls of the equipment being used. The two pH values that are equal produce similar results, showing the reproducibility of the experiment.

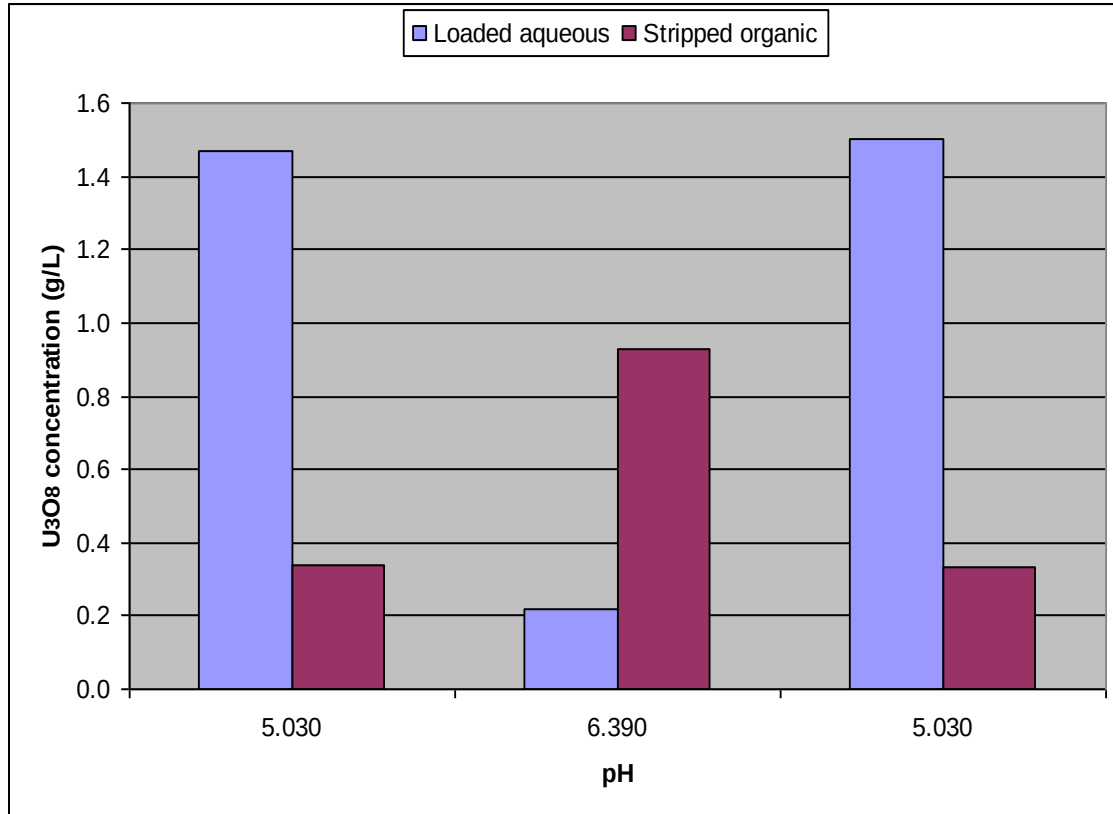


Figure 4-12: pH effect on the Biodiesel solvent

Table 4-7 once again shows that the rate of NH_4OH addition has a substantial effect on the volume of NH_4OH that has to be added to reach a specific pH. A pH value of less than or equal to 5 shows the best overall results for pH stripping. Therefore the pH was kept as close as possible to 5 for the experimental procedure 2 stripping experiments.

Table 4-7: SSX 210 stripping characteristics

pH	Volume	Tempo
5.03	6.7 mL	Moderate
5.03	7.2 mL	fast
6.39	8.6 mL	fast

The residence time of the stripping phase will determine the overall rate at which the NH_4OH can be added in practice. This will influence the size of the selected equipment (equipment capacity) and this, in turn, will determine whether or not the desired pH will be reached. In the final chapter, recommendations will be made on further investigations to clarify the pH effect on the stripping stage of the SX process.

Overall, the SSX 210 showed the highest concentration U_3O_8 being stripped. This served as a major motivator to proceed to experimental procedure 2 of the overall experimental investigation using SSX 210.

4.3.2 Diluent composition pH observations

Comparative analysis of the varying solvent compositions and the effect this has on the stripping characteristics, with regard to pH, are shown in figure 4-13. The rate of nucleation and the rate of growth of the uranium complex is dependent on the uranium concentration, which is the driving force for the reaction.

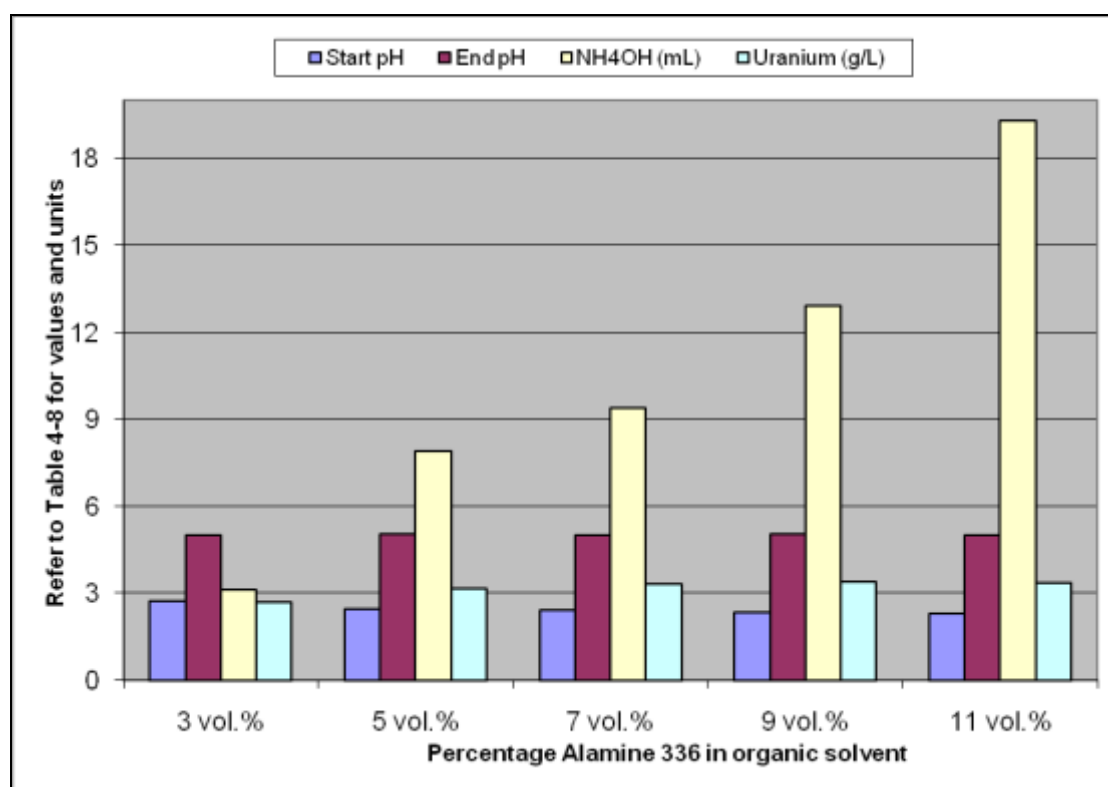


Figure 4-13: Comparative analysis of the varying solvent compositions

Figure 4-13 shows the overall effect, while table 4-8 assists the reader to base a decision on numeric values. A clear observation is the increase in the volume of NH_4OH required to strip the uranium from a solvent with a higher Alamine 336 volume percentage content. At this stage the assumption was made that the original

solvent composition (5 vol.% Alamine 336, 2 vol.% isodecanol and 93 vol.% diluent) remains the most effective, especially when reagent prices for isodecanol, Alamine 336 and NH_4OH are considered. However, the solvents with higher Alamine 336 content allowed more U_3O_8 to be loaded to the aqueous OK Liquor.

Table 4-8: Data used for compilation of figure 4-13

Stripping pHs				
Alamine 336	Start pH	End pH	NH_4OH	U_3O_8
(vol.%)			(mL)	(g/L)
3	2.74	5.01	3.1	2.690
5	2.45	5.02	7.9	3.175
7	2.43	5.00	9.4	3.295
9	2.34	5.02	12.9	3.375
11	2.3	5.00	19.3	3.370

4.4 Experimental procedure 4: Precipitation evaluation

The final procedure of the experimental process was a precipitation experiment to identify the influence that the newly selected diluent would have on the precipitation product composition and structure. Experimental procedure 1 was carried out with 5 vol.% Alamine 336, 2 vol.% isodecanol and 93 vol.% SSX 210 composition. The pH was raised to exactly 5 during the stripping procedure, and the OK Liquor was handed over to a fellow researcher running precipitation experiments at the South Uranium Plant. For detail on the experimental setup, see van Rhyn (2009). The reason why this procedure was used, was to enable a comparison between the OK Liquor generated with SSX 210, and the OK Liquor generated by the South Uranium Plant (using kerosene as diluent). Only a single run of this experiment could be conducted as a result of the restricted amount of SSX 210 available. Table 4-9 shows the parameters involved in the setup of this experimental run.

Table 4-9: Precipitation parameters for experimental procedure 4

Precipitation input parameters	
Temperature	42°C
Stirrer	50 rpm
Ammonia flow rate	5 L/h
Ammonia purity	99%
Air flow rate	1.5 L/h

The experiment was run and a visible formation of the ADU precipitate could be seen through the glass vessel. A SEM analysis was then conducted on the SSX 210 ADU precipitation sample. The particle structure was amorphous and the average size of the particles was $\pm 2000 \mu\text{m}$. All the elements analysed were normalised and the composition is given in mass percentages in table 4-10.

A sample generated by van Rhyn, with which the SSX 210 sample could be compared was obtained. The precipitation conditions for the two samples were exactly the same, as were the conditions of the SEM analysis (including magnification) conducted. The result of the SEM analysis is shown as micrographs in figures 4-14 and 4-15.

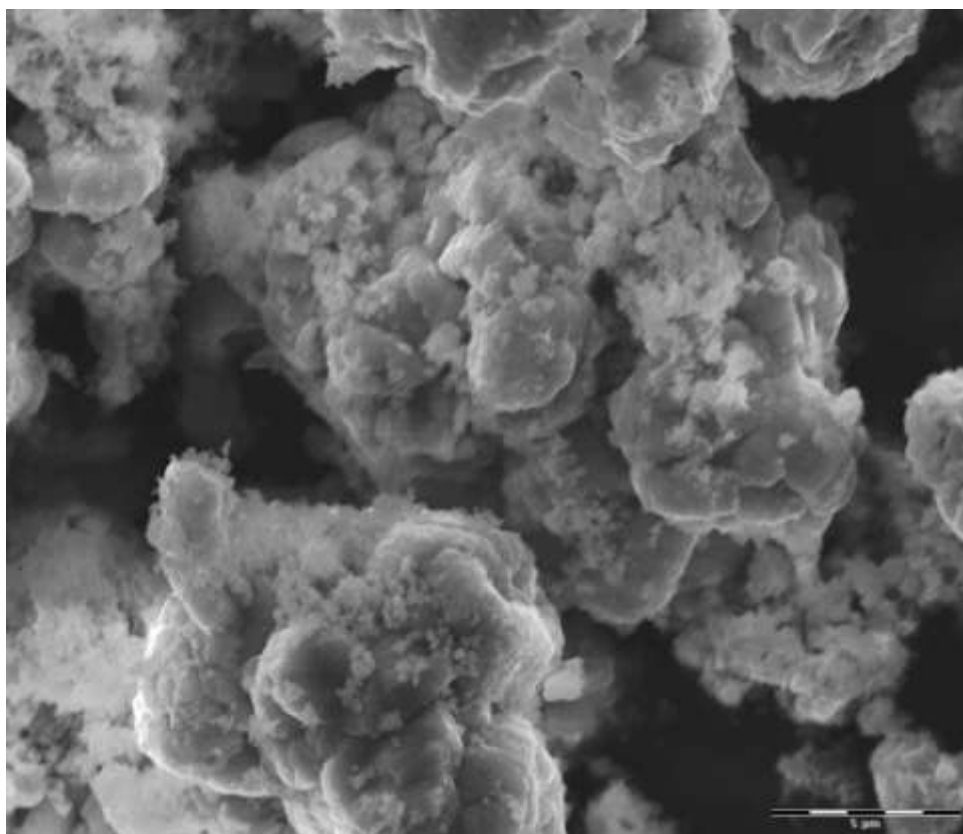
**Figure 4-14: Precipitation sample of kerosene OK Liquor**

Figure 4-14 shows the dried precipitated amorphous ADU particles of the OK Liquor generated using kerosene as a diluent for the solvent. The ADU particles are in agglomerated formation, with fine particles residing on these ADU agglomerates. The composition of this sample is given in table 4-10, and is also compared with the composition of the SEM analysis result in figure 4-15.

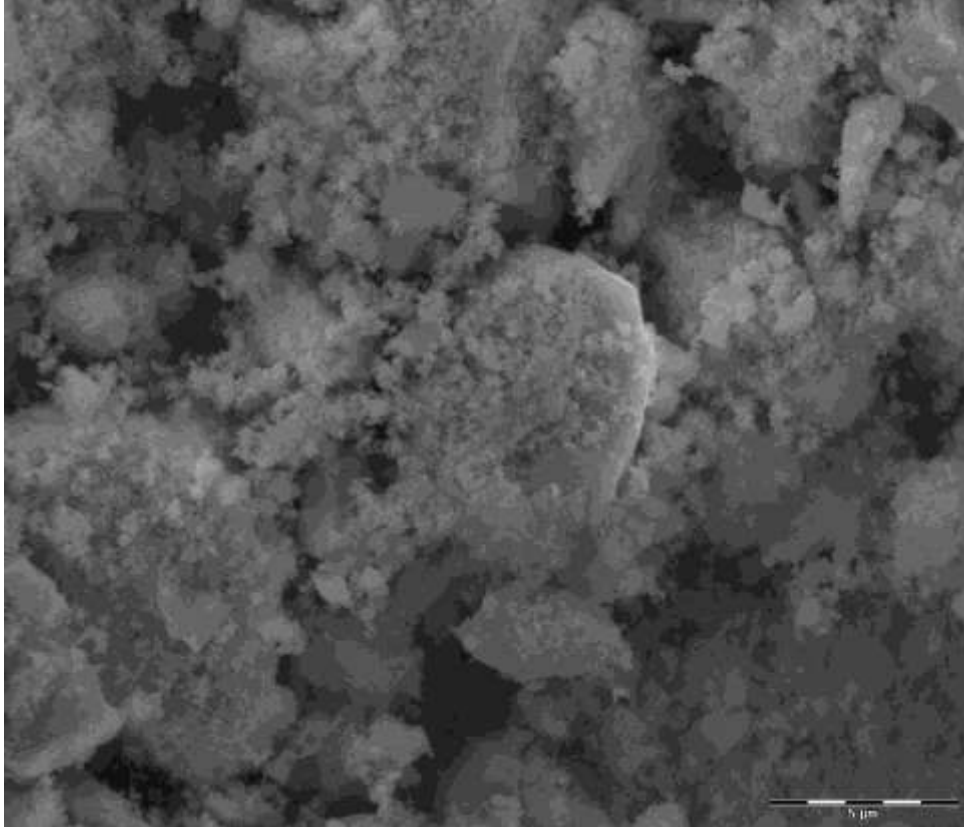


Figure 4-15: SSX 210 OK Liquor precipitation sample

Figure 4-15 shows the dried precipitated amorphous ADU particles of the OK Liquor generated using SSX 210 as a diluent for the solvent. The ADU particles are in agglomerated formations, but the shape appears to differ considerably from the sample generated with OK Liquor from the plant (which uses kerosene). The fine particles residing on the agglomerated ADU particles appear to have been spread out more evenly, and the density of the agglomerations and fine particles appears to have increased.

The two results from the SEM analyses are compared in table 4-10, to illustrate the differences in the elemental composition of each ADU sample.

Table 4-10: Comparison of OK Liquor sample composition

	Kerosene ADU sample	SSX 210 ADU sample
Element	Composition (mass %)	Composition (mass %)
C	3.97	5.68
N	7.65	8.82
O	24.68	25.86
S	3.50	3.02
U	60.2	56.62
Total	100	100

A lower uranium yield was obtained from the SSX 210 OK Liquor sample, and the overall conclusion is that kerosene is still the more efficient diluent in the range that was considered, when only considering product yield. In the laboratory, SSX 210 appears to be a good alternative if the plant is forced to reconsider the SHE characteristics. Another option not investigated is the diluent used by Rössing Uranium in Namibia - Shellsol 2325. The reason for not investigating this diluent was because more reliable and decisive data can be obtained from the actual Rössing Uranium plant. However, the plants do not operate under the same conditions, which would make a direct comparison between the Lurgi design of the South Uranium Plant and the design of the Rössing Uranium plant unfeasible.

4.5 Data summary

The complete data set for all the experimental work discussed in Chapter 4 is included in Appendices A to E. An electronic copy of all the data as generated and processed in the laboratory, is available at the Ferdinand Postma library of the North-West University.

4.6 Statistic evaluation

All the data were analysed using the statistics computer package Statistica version 8.0, by Professor Faans Steyn, a statistics consultant from the Department of Statistics Consultation, North-West University. The report is included in Appendix G. The charts in this report include an upper and lower confidence limit, which indicate the range of the 95% confidence interval visually. Overall, the standard deviations and reliability of the data were deemed acceptable.

5 Conclusions and recommendations

5.1 Experimental procedure 1: Diluent selection

5.1.1 Conclusion

The goal of experimental procedure 1 was to select a diluent from four alternative options. SSX 210 was chosen as it had the most favourable physical properties, and delivered an acceptable product yield. The conclusion was based on a comparative analysis, and SSX 210 performed the best in terms of overall criteria requirements.

During the final stages of writing this report, verbal communication was received that the diluent was experimented with on industrial level at the Rössing Uranium plant in Namibia. The results of the implementation of this diluent were not favourable, as a third phase had formed and the product could not be efficiently extracted (Louw, 2009). The possible reasons for this (differing from the laboratory findings) are unaccounted-for factors in an industrial application that cannot be simulated in a laboratory setup. The physical properties of SSX 210 still remain highly desirable. Because the functionality of the plant would be hampered, the option is, nonetheless, automatically disqualified for the Rössing industrial implementation. The suspected reason for the formation of the third phase in the industrial test run on SSX 210 at Rössing is because of the U-complex's inability to solvate fully in the organic phase. It is well known that aromatic-containing diluents solvate large complexes far more effectively than straight chain aliphatics. This is the main reason that aromatics are usually used for high molecular weight metals (such as U, Pt, Pd, etc.) while aliphatics are used for lower molecular weight complexes (such as Ni, Co, Cu, etc.). The Shellsol 2325 currently in use at Rössing has a 20% aromatic content – which prevents the formation of the third phase.

A higher content of modifier can help the solvation to some extent, but the organic composition will be a compromise of various competing factors.

5.1.2 Recommendation

The commissioning of a new SX section with a higher throughput capacity at the South Uranium Plant is foreseen for the immediate future (du Plessis, 2009). A pilot plant-scale test of the SX section with the newly selected diluent used in the solvent is not recommended. This is based on the similarities between the two uranium plants under discussion.

The unfavourable results for using SSX 210 at Rössing, the similarities between it and the South Uranium Plant need to be considered. The ore composition differs considerably, but the feed liquors entering the SX stage of the two facilities under discussion is similar in composition, with the Rössing liquor containing a higher concentration uranium and minor differences in impurities. The solvent used at Rössing is 7 vol.% Alamine 336 and 3 vol.% isodecanol in Shellsol 2325, and the plant has two trains of five extraction stages. The loaded organic from both trains is combined and scrubbed in two scrub stages. Scrubbed organic is stripped with ammonium sulfate at a pH of 4.2 in four strip stages. The pH adjustment in the strip circuit is also conducted by addition of ammonium hydroxide. The OK Liquor contains 15–16 g/L uranium, which is considerably higher than the OK Liquor produced by the South Uranium Plant (Sole et al., 2005). The difference in process equipment and number of different stages for the extraction, scrubbing and stripping sections is not the reason why the outcome with SSX 210 might be different at the two plants, because SX is an equilibrium process.

Shellsol 2325 contains 16-23% aromatics, which is already an improvement on the kerosene currently used by the South Uranium Plant. It should be noted that there are some very favourable physical and chemical properties in the SSX 210 that remain an improvement over the Shellsol 2325 used at Rössing in Namibia.

Another recommendation would be a techno-economic evaluation of the Shellsol 2325 and SSX 210 diluents. The SSX 210 is considerably more expensive option at ±R 12/L, compared to kerosene at ±R 8,50/L. (Price information supplied by ChemQuest on average prices during 2008-2009 financial year.)

5.2 Experimental procedure 2: Solvent composition

5.2.1 Conclusions

The goal of experimental procedure 2 was to find an optimal solvent composition for the diluent, the extractant and the third-phase inhibitor. It was found that the composition currently used by the plant still produces the best empirical results. However, as noted in the conclusion of experimental procedure 1, the industrial application results can differ largely from results obtained in a laboratory.

5.2.2 Recommendations

A recommendation would be to evaluate the inadequately explained unexpected behaviour of the 11 vol.% Alamine 336 composition. If it is only a case of an extreme outlier experimental data point, this should be confirmed; otherwise a valid theoretical explanation should be sought.

Because of the formation of a third phase at the Rössing plant, it would be recommended that the percentage composition of isodecanol also be optimised, especially if the SSX 210 diluent is tested on a pilot plant or continuous bench scale with plant eluate feed. Increasing the third-phase modifier may also be an option for improving phase separation and avoiding third-phase formation when using a less aromatic diluent.

5.3 Experimental procedure 3: pH investigation

5.3.1 Conclusions

As mentioned earlier, the commissioning of a new SX section with a higher throughput capacity at the South Uranium Plant is foreseen for the immediate future (du Plessis, 2009). The pH control will be a parameter that significantly influences equipment selection considerations for the new SX section. As shown in section 4.3, the pH is a highly influential parameter for obtaining the desired product.

The Bateman pulsed column is a popular next-generation equipment design (not only applicable to uranium) that aims to replace the conventional mixer-settler setup of older SX sections.

Column contactors claim the following advantages (Mackenzie, Undated):

- Low area requirements
- Multiple stages within one unit
- Few moving parts
- Low entrainment
- Good vapour conservation

These columns have been implemented in Australia (WMC Olympic Dam) and South Africa (Dominion Reef), with varied success. Some of the less favourable aspects are:

- Column installations require piloting for each installation and the flooding conditions for the column must be determined
- Long residence times in a column compared to a mixer-settler can influence the selectivity of the extraction if contaminants have slow extraction kinetics.

In the case of the South Uranium Plant, the implementation of precise pH control in this closed vessel poses a problem due to the sensitivity of the stripping efficiency to pH changes.

5.3.2 Recommendations

It is recommended that Bateman pulsed columns be considered to replace the extraction mixer-settlers, since the pH is not adjusted intentionally in this section of the SX equipment setup. The scrubbing efficiency of conventional equipment must be evaluated from a techno-economical perspective, to decide whether the increased cost of more specialised and more expensive equipment justifies the possible improvement or its associated benefits. However, because of the overall sensitivity of the stripping section to pH, it is not recommended to replace the equipment currently in use for this section. It is instead recommended that the method of pH control and NH_4OH addition be optimised in the current stripping circuit.

5.4 Experimental procedure 4: Precipitation

5.4.1 Conclusions

It was shown that an ADU precipitate could be formed from an OK Liquor generated with SSX 210 inclusion in the process. There was, however a clear physical difference in the ADU particles formed by the kerosene process and those formed by a SSX 210 process. The composition of the ADU particles also contained less of the desired uranium.

5.4.2 Recommendations

It should be determined if the particle structural difference will have a negative impact on the process steps to be followed. A thorough precipitation investigation should be conducted if SSX 210 is found to be useful as a possible diluent.

5.5 General recommendations

Amines form complexes directly with both sulfate and bisulfate anions. The loading and stripping of these species were not mentioned; as such detailed analysis could not be facilitated under the experimental conditions. In general, complexation with uranyl sulfate is stronger, but when there is excess capacity available on the organic phase (e.g., under conditions of high extraction concentration), sulfate and bi-sulfate will also load.

Future experimental work to conduct more detailed analysis on a single chosen diluent for determining an extraction isotherm and measuring the maximum loading capacity of uranium is recommended. This would indicate whether other species are also loading relative to the loading expected from the reaction stoichiometry. Experience from other research is that 20% to 30% of the organic capacity is taken up by species other than uranium.

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Appendix A

Material Safety Data Sheets

These are available for further reference. The documents were not modified and are included in their original format as obtained from the literature sources.

The order of appearance is as follows:

- Kerosene
- Biodiesel B-100
- Sasol Wax SSX 150
- Sasol Wax SSX 210
- Shellsol D70
- Shellsol 2325

Appendix B

Data sheet: Experimental procedure 1

Table B-1: Data sheet of analysis results for experimental procedure 1

 ANGLOGOLD ASHANTI Job No : STUDENT_05082009 Date received: 08/14/09 Date reported: 16 November 2009			
Sample Identification	U3O8	SO4	Fe
KSE 1 AQU	0.216	92.56	0.773
KSE 2 AQU	0.217	92.90	0.783
KSE 3 AQU	0.223	94.16	0.790
KOK 2 AQU	1.140	91.02	0.002
KOK 3 AQU	0.176	94.36	<0.002
KOS 1 AQU	<0.002	3.29	0.004
KOS 2 AQU	<0.002	2.85	0.004
KOS 3 AQU	<0.002	2.20	0.003
E 1 AQU	2.560	100.30	0.796
E 2 AQU	3.02	68.89	0.896
E 3 AQU	3.04	67.96	0.902
(NH4)2SO4 AQU	0.002	90.33	0.002
XOS 1 AQU	<0.002	3.02	0.005
XOS 2 AQU	<0.002	2.77	0.004
XOS 3 AQU	0.002	2.37	0.003
XSE 1 AQU	0.264	90.26	0.795
XSE 2 AQU	0.268	91.13	0.786
XSE 3 AQU	0.273	92.03	0.791
XOK 1 AQU	1.370	89.80	0.002
XOK 2 AQU	1.760	90.12	<0.002
XOK 3 AQU	0.453	89.24	<0.002
YSE 1 AQU	0.287	93.95	0.762
YSE 2 AQU	0.288	93.75	0.754
YSE 3 AQU	0.294	92.58	0.742
YOS 1 AQU	0.002	3.69	0.009
YOS 2 AQU	<0.002	14.22	0.006
YOS 3 AQU	<0.002	2.35	0.005
YOK 1 AQU	1.170	89.42	<0.002
YOK 2 AQU	1.890	91.93	<0.002
YOK 3 AQU	1.050	90.43	<0.002
BSE 1 AQU	0.435	91.52	<0.002
BSE 2 AQU	0.454	92.20	0.871
BSE 3 AQU	0.432	91.44	0.781
BOS 1 AQU	0.003	4.17	0.016
BOS 2 AQU	<0.002	2.78	0.009
BOS 3 AQU	0.002	2.21	0.007
BOK 1 AQU	1.470	87.40	<0.002
BOK 2 AQU	0.218	88.86	<0.002
BOK 3 AQU	1.500	89.84	<0.002
DSE 2 AQU	0.295	92.75	0.706
KLO 1 ORG	3.232	11.76	
KLO 2 ORG	3.040	9.27	

(continues)

KLO 3 ORG	2.840	9.34	
XLO 1 ORG	3.036	11.71	
XLO 2 ORG	3.016	9.67	
XLO 3 ORG	3.012	8.18	
KSTO 2 ORG	0.021	1.02	
KSTO 3 ORG	0.028	0.19	
XSTO 1 ORG	0.008	1.07	
XSTO 2 ORG	0.590	1.30	
XSTO 3 ORG	0.013	<10	
DLO 2 ORG	3.024	8.48	
BSTO 1 ORG	0.336	1.13	
BSTO 2 ORG	0.929	1.03	
BSTO 3 ORG	0.331	1.10	
BLO 1 ORG	2.594	11.61	
BLO 2 ORG	2.496	9.78	
BLO 3 ORG	2.512	0.16	
YLO 1 ORG	3.174	7.81	
YLO 2 ORG	2.986	10.53	
YLO 3 ORG	3.116	8.61	
YSTO 1 ORG	0.005	0.38	
YSTO 2 ORG	0.345	0.56	
YSTO 3 ORG	0.013	<10	
	G/L	G/L	G/L

Appendix C

Experimental procedure 1: Diluent selection

Diluent effect on U_3O_8 concentration

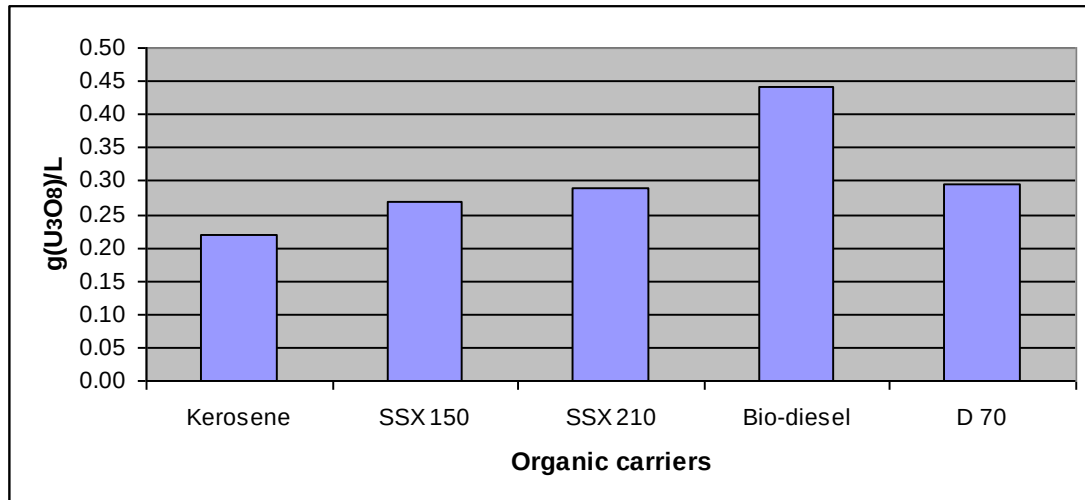


Figure C-1: U_3O_8 concentration in aqueous phase during extraction step

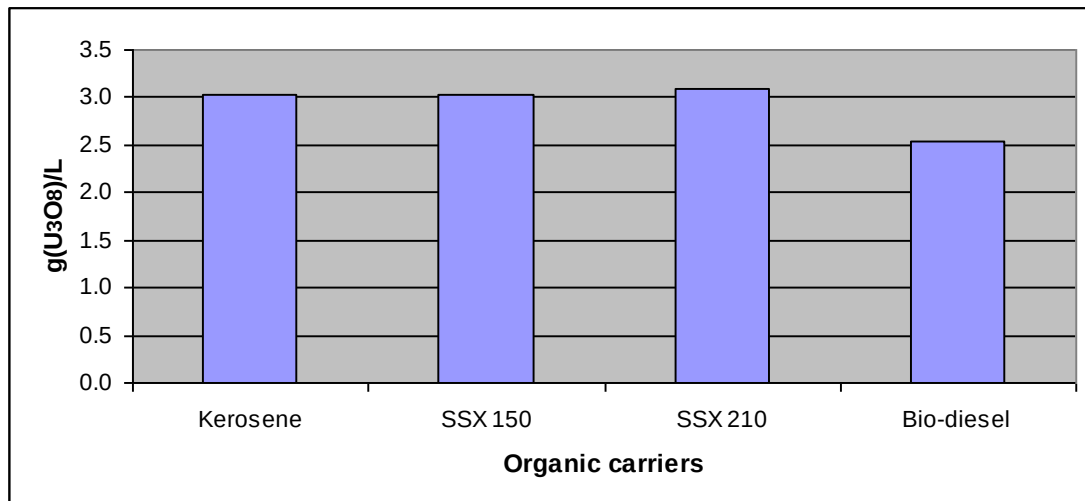


Figure C-2: U_3O_8 concentration in organic phase during extraction step

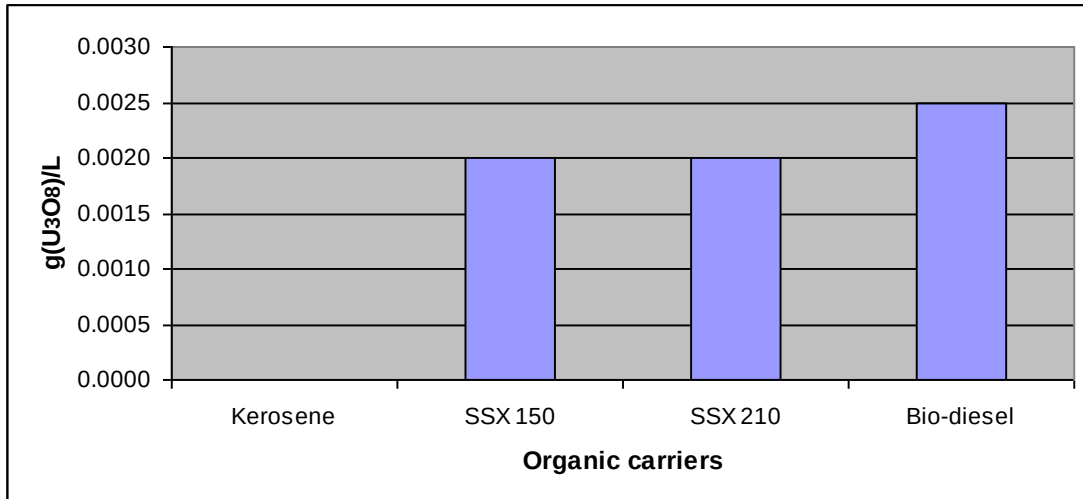


Figure C-3: U₃O₈ concentration in aqueous phase during scrubbing step

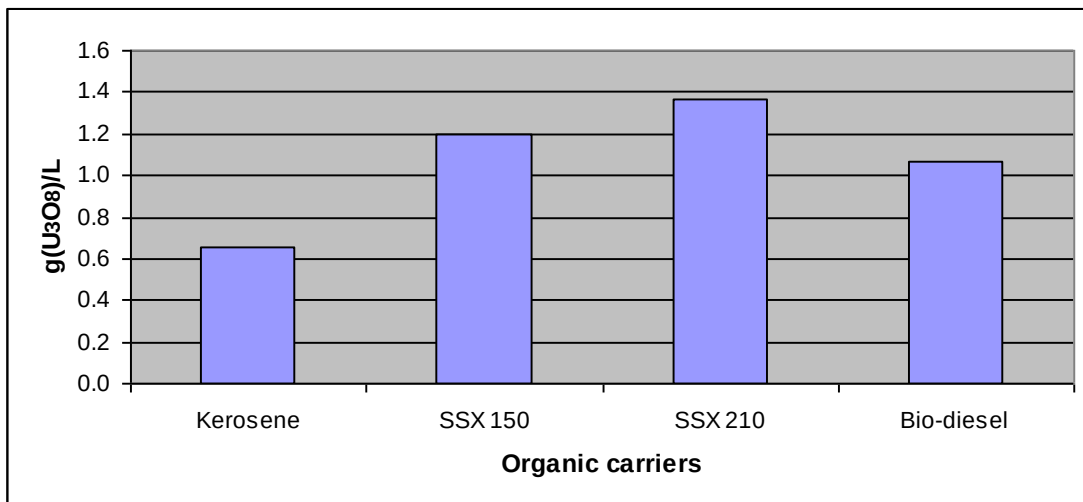


Figure C-4: U₃O₈ concentration in aqueous phase during stripping step

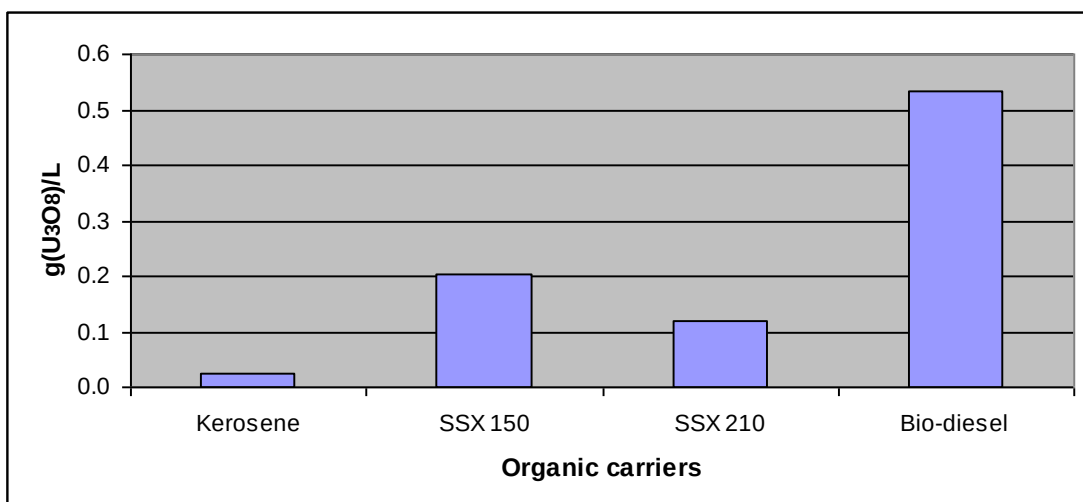


Figure C-5: U₃O₈ concentration in organic phase during stripping step

Diluent effect on SO_4 concentration

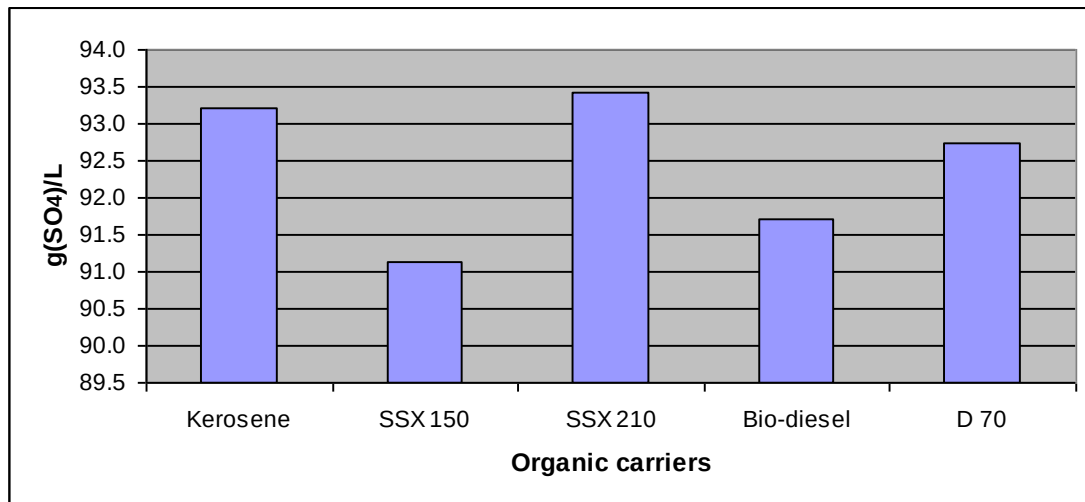


Figure C-6: SO_4 concentration in aqueous phase during extraction step

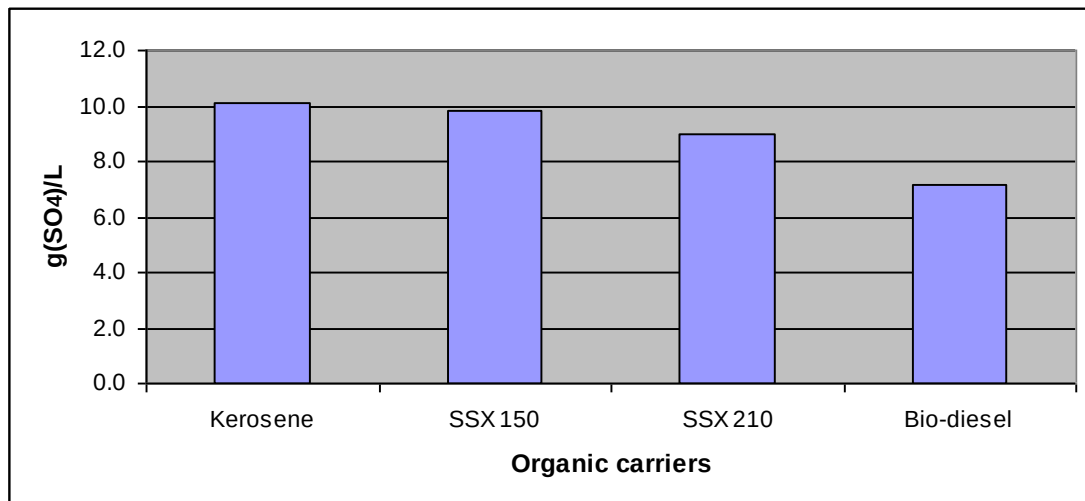


Figure C-7: SO_4 concentration in organic phase during extraction step

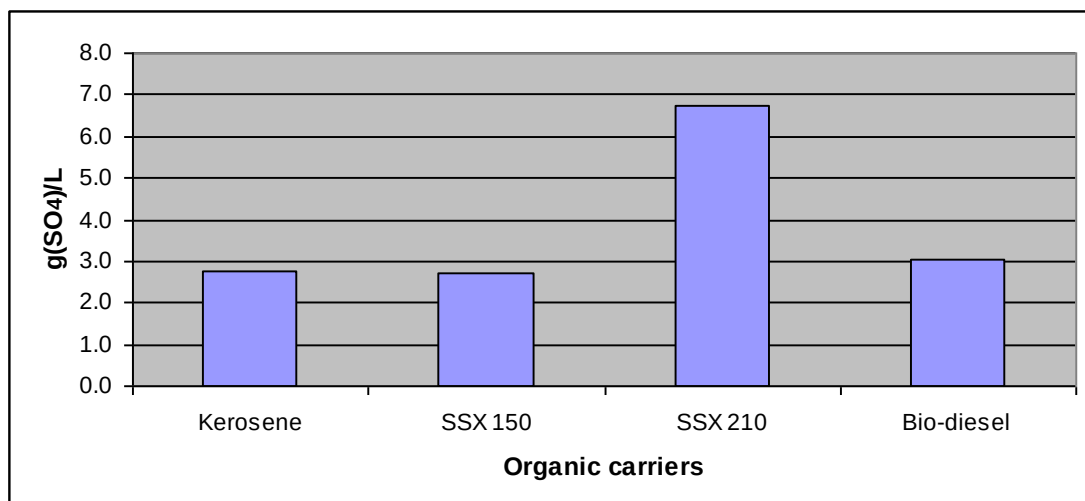


Figure C-8: SO_4 concentration in aqueous phase during scrubbing step

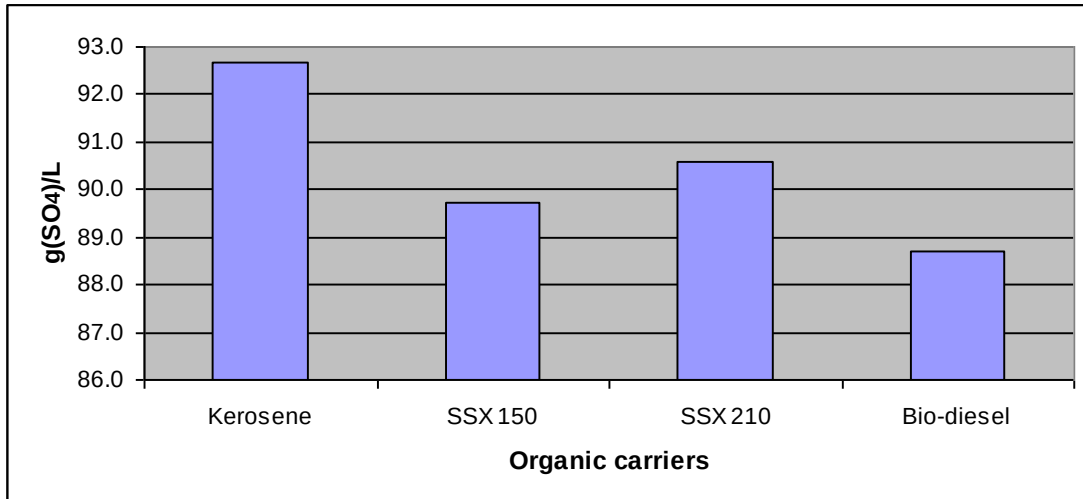


Figure C-9: SO_4 concentration in aqueous phase during stripping step

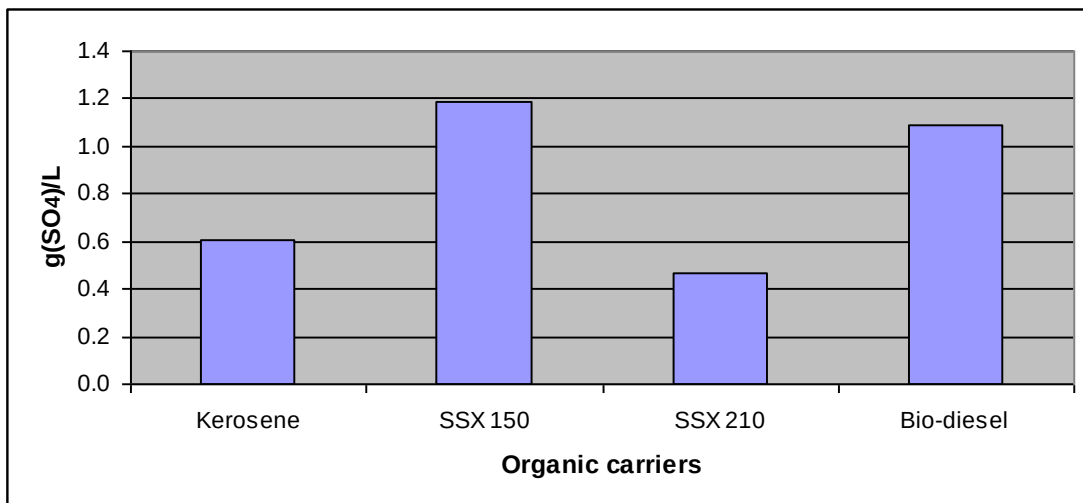


Figure C-10: SO_4 concentration in organic phase during stripping step

Diluent effect on Fe concentration

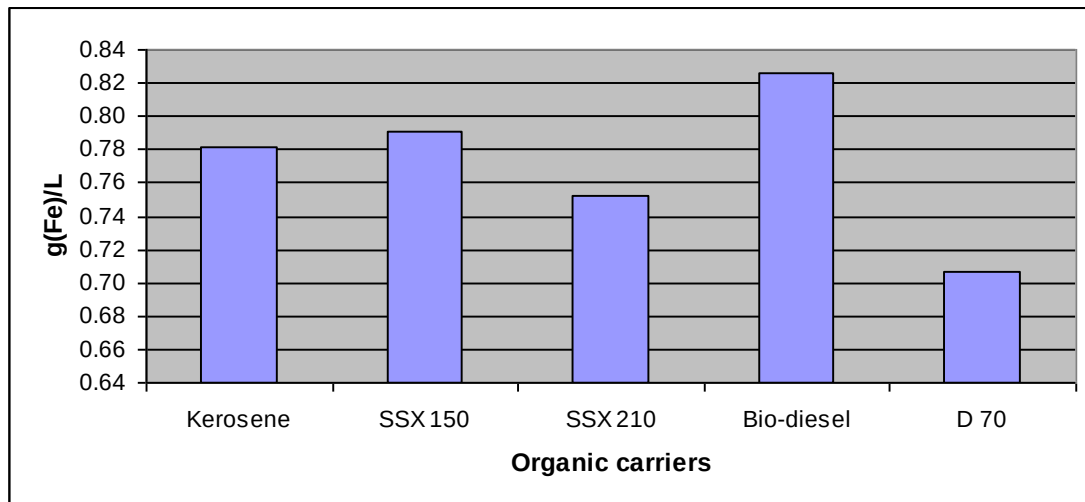


Figure C-11: Fe concentration in aqueous phase during extraction step

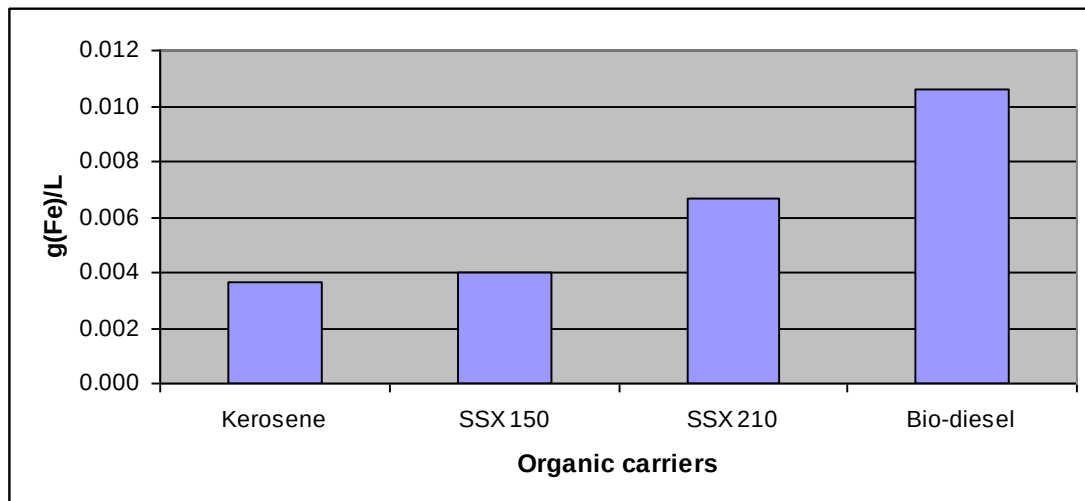


Figure C-12: Fe concentration in aqueous phase during scrubbing step

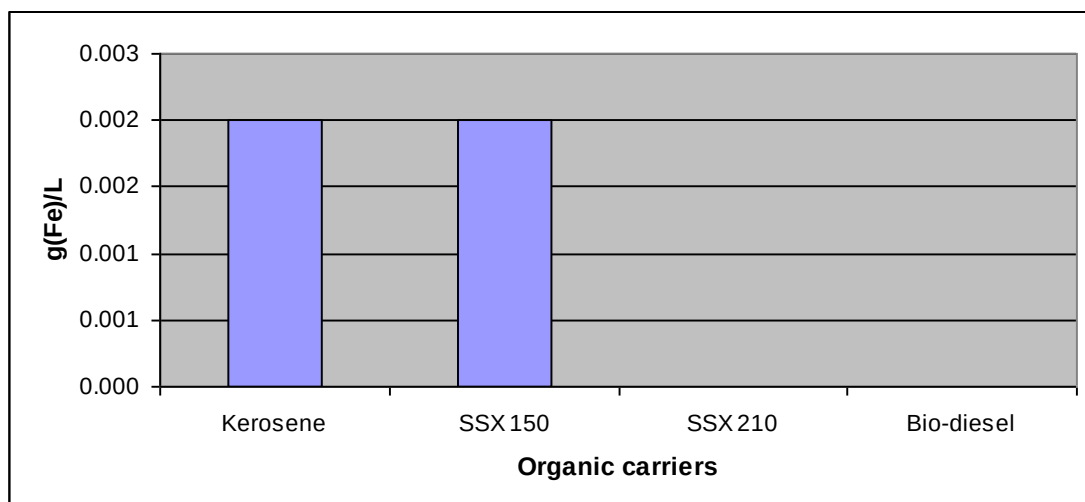


Figure C-13: Fe concentration in aqueous phase during stripping step

Appendix D

Data set: Experimental procedure 2

Table D-1: Data sheet of analysis results for experimental procedure 2

 ANGLOGOLD ASHANTI			
Job No : STUDENT_10092009			
Date received:			
Date reported:			
Sample Identification	U3O8	SO4	Fe
(NH4)2SO4 AQU	<0.002	90	<0.002
AE 3 AQU	0.652	96	854.66
AE 5 AQU	0.296	101	892.17
AE 7 AQU	0.175	91	897.17
AE 9 AQU	0.126	109	868.49
AE 11 AQU	0.088	93	897.02
AS 3 AQU	1.250	94	1.96
AS 5 AQU	2.450	90	0
AS 7 AQU	1.890	91	0
AS 9 AQU	1.780	88	0
AS 11AQU	2.06	110	0
S3 AQU	0.019	2	3.77
S5 AQU	0	4	2.76
S7AQU	0	5	3.22
S9 AQU	0	4	5.31
S11 AQU	0	5	4.28
OE 3 ORG	2.690	8	
OE 5 ORG	3.175	11	
OE7 ORG	3.295	16	
OE9 ORG	3.375	21	
OE11ORG	3.370	3	
OS 3 ORG	0.003	1	
OS 5 ORG	0.003	3	
OS 7 ORG	0.017	5	
OS9 ORG	0.025	3	
OS11 ORG	0.034	5	
	G/L	G/L	G/L

Appendix E

Experimental procedure 2: Solvent optimisation

Composition effects on U_3O_8

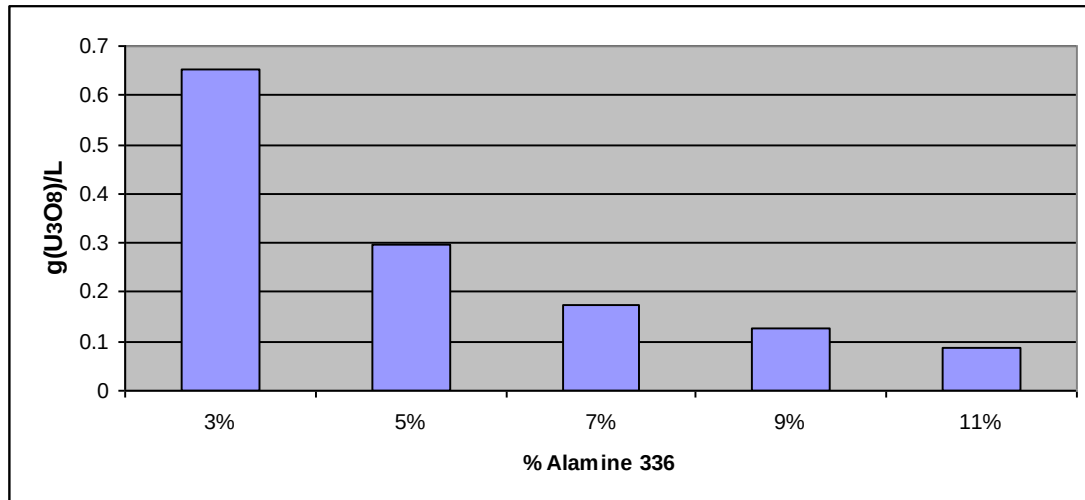


Figure E-1: U_3O_8 concentration in the aqueous extraction optimisation stage

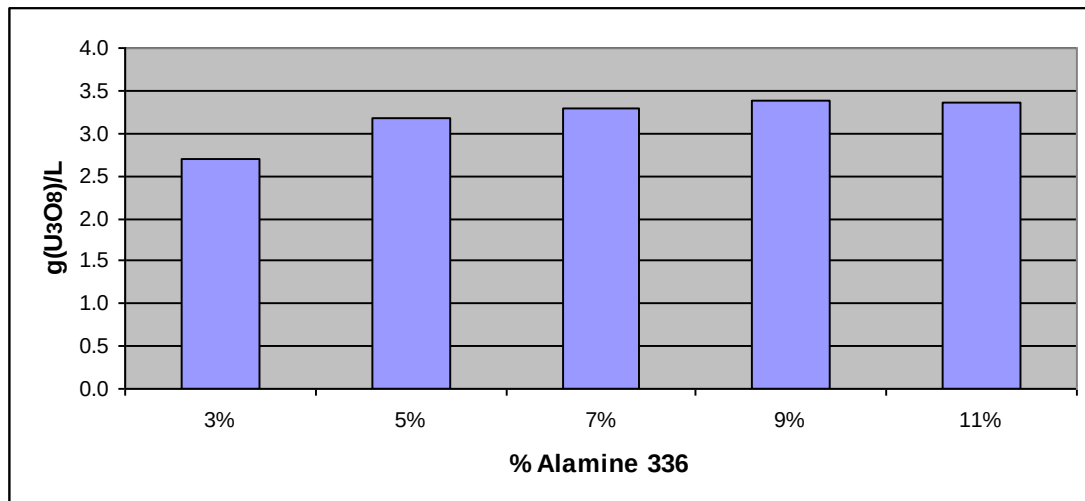


Figure E-2: U_3O_8 concentration in the organic extraction optimisation stage

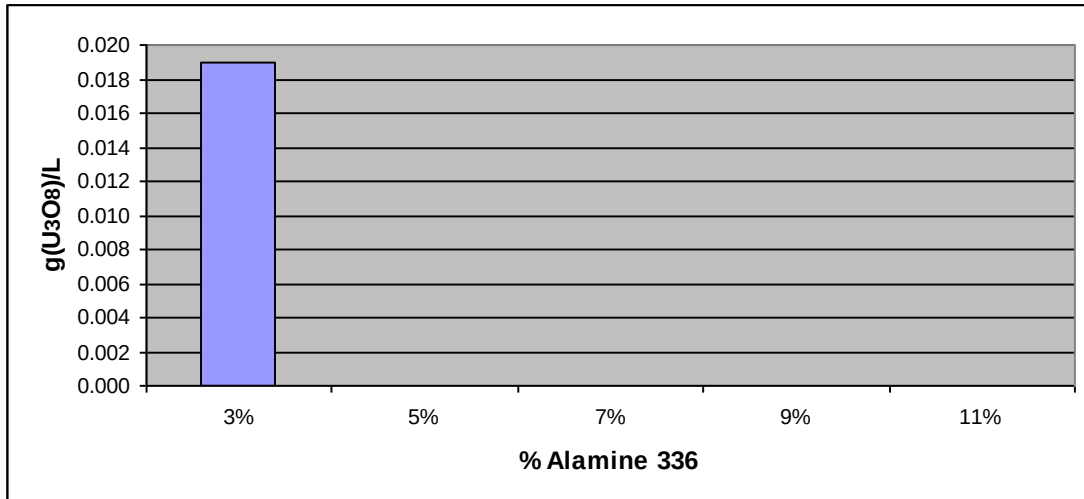


Figure E-3: U_3O_8 concentration in the aqueous scrubbing optimisation stage

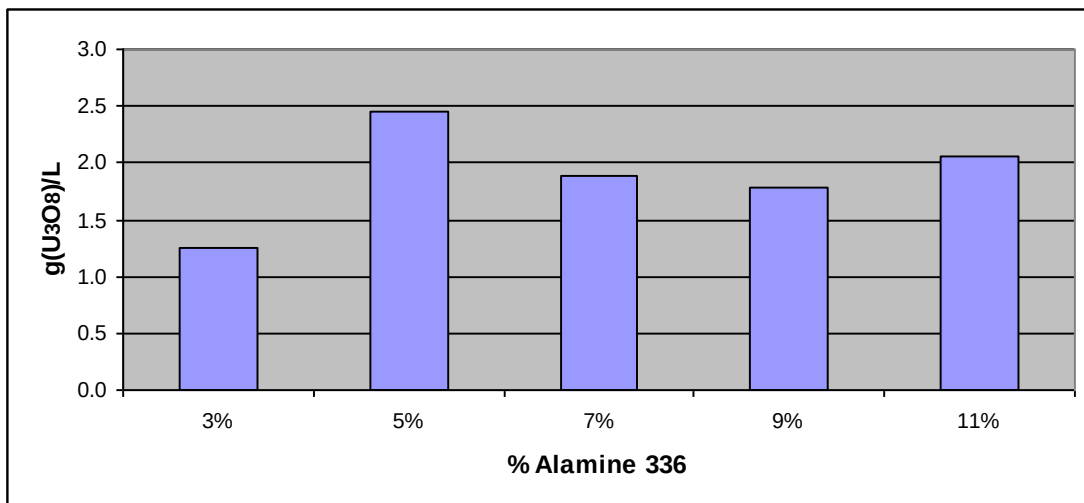


Figure E-4: U_3O_8 concentration in the aqueous stripping optimisation stage

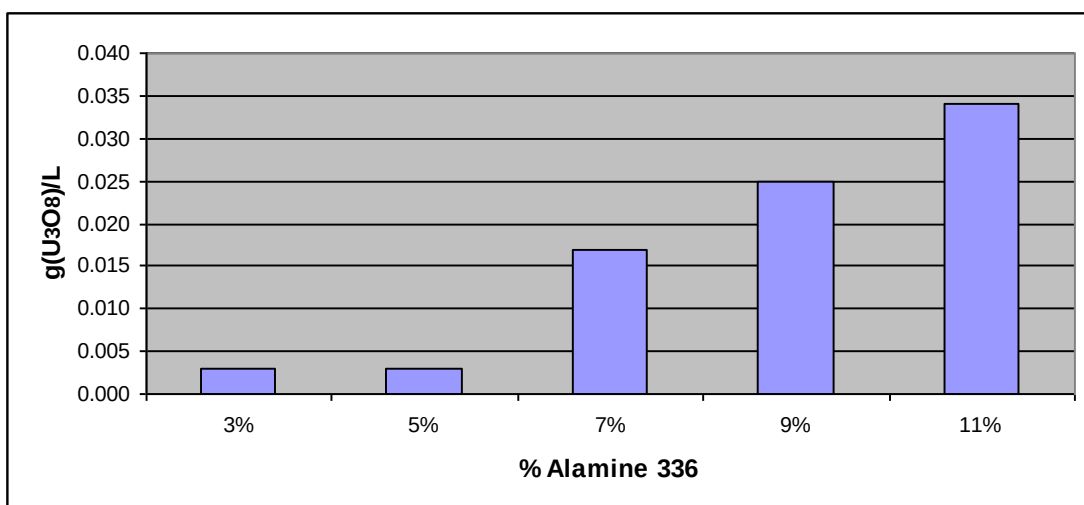


Figure E-5: U_3O_8 concentration in the aqueous stripping optimisation stage

Composition effects on SO_4

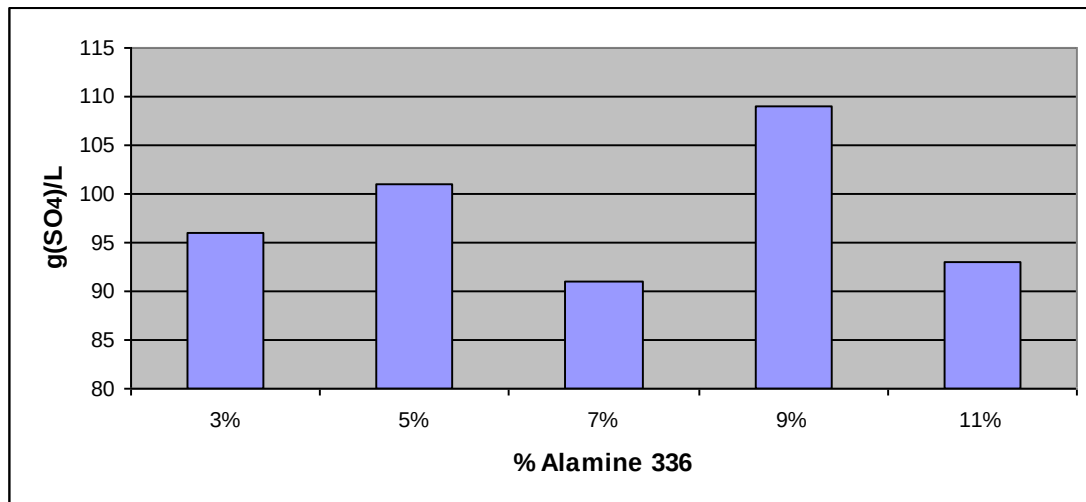


Figure E-6: SO_4 concentration in the aqueous extraction optimisation stage

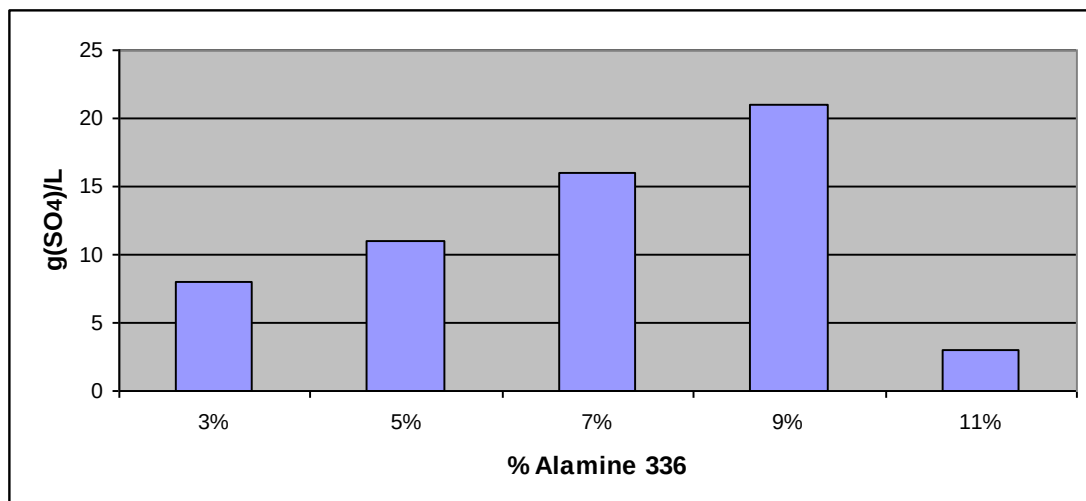


Figure E-7: SO_4 concentration in the organic extraction optimisation stage

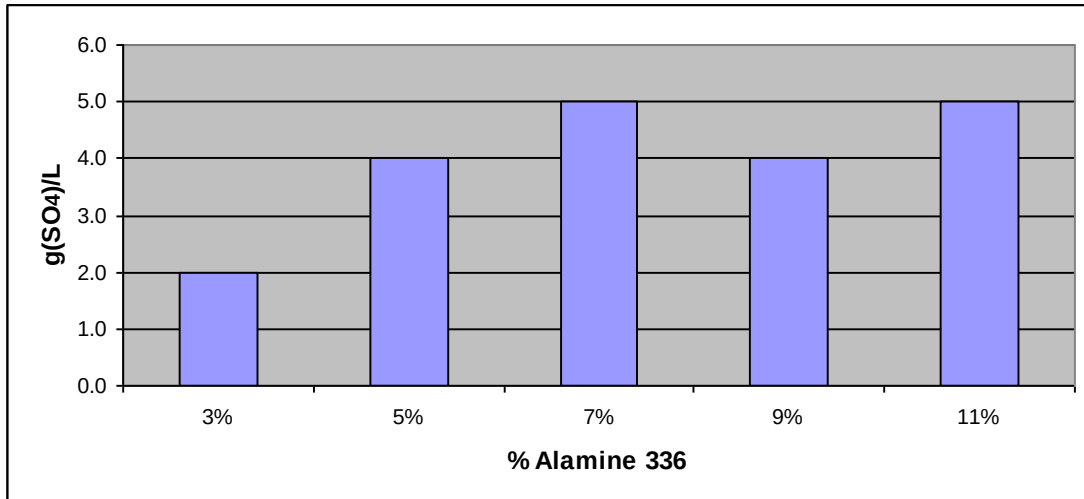


Figure E-8: SO_4 concentration in the aqueous scrubbing optimisation stage

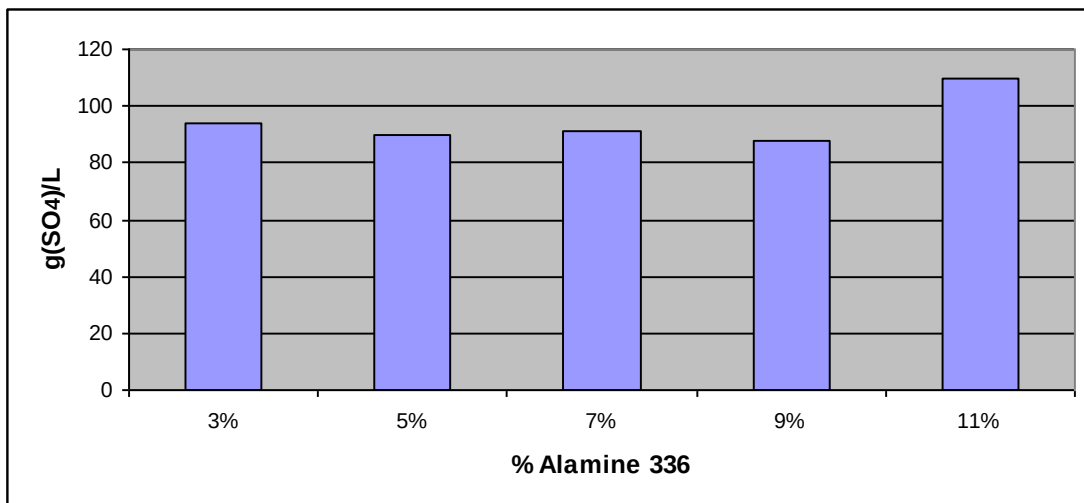


Figure E-9: SO_4 concentration in the aqueous stripping optimisation stage

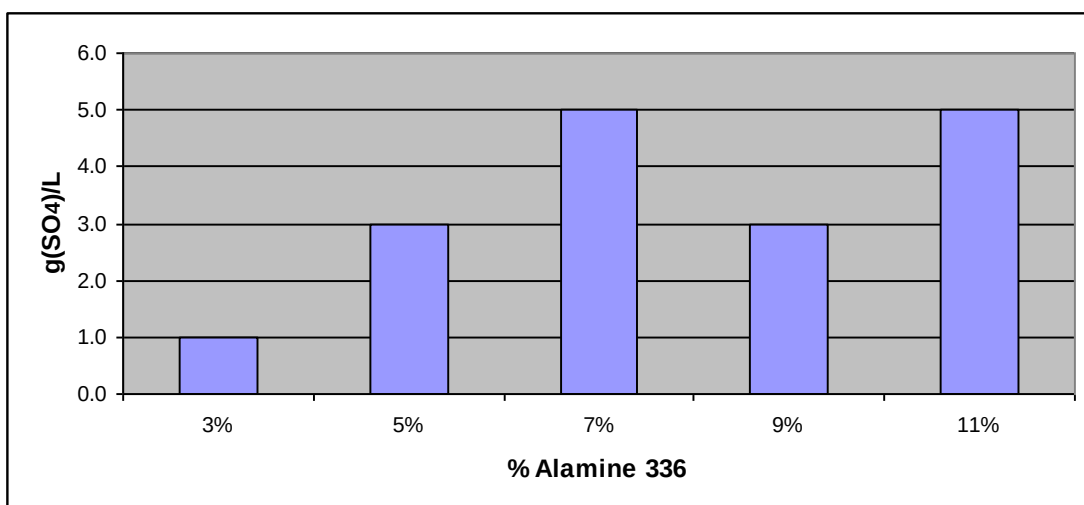


Figure E-10: SO_4 concentration in the organic stripping optimisation stage

Composition effects on Fe content

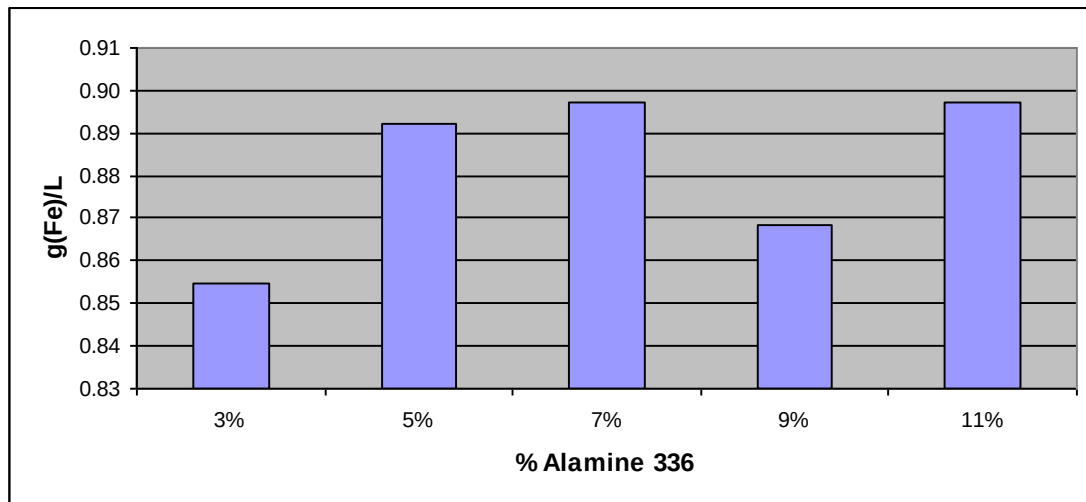


Figure E-11: Fe concentration in the aqueous extraction optimisation stage

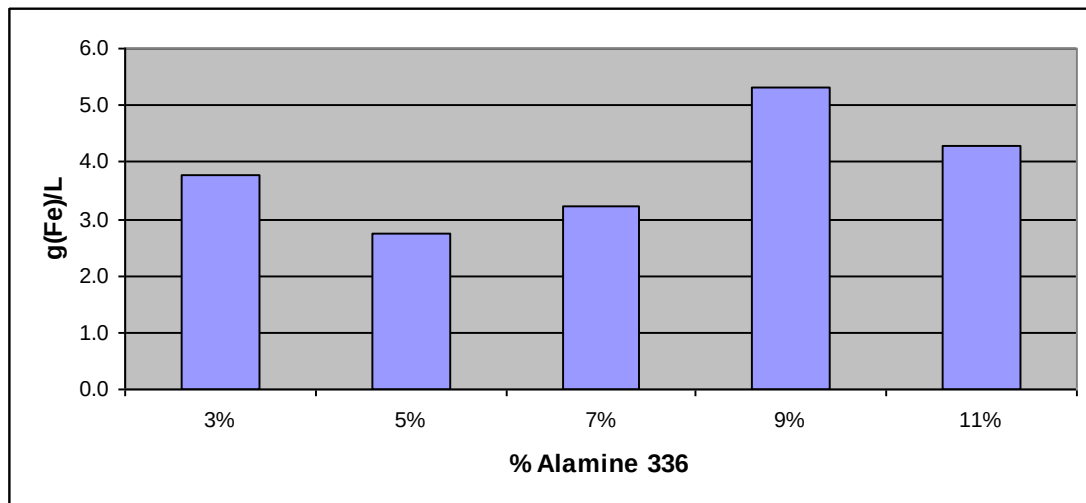


Figure E-12: Fe concentration in the aqueous scrubbing optimisation stage

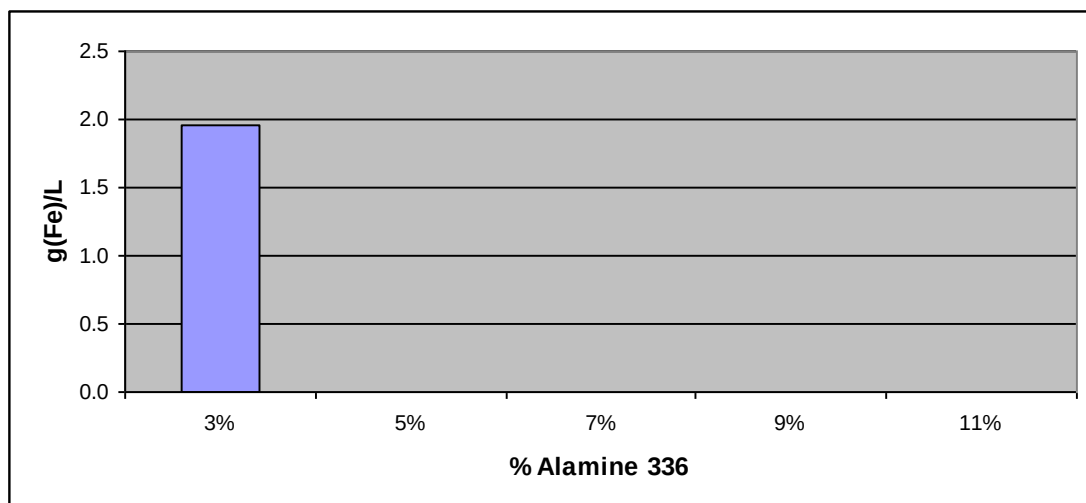


Figure E-13: Fe concentration in the aqueous stripping optimisation stage

Appendix F

Experimental procedure 3: pH characteristics

The following four graphs indicate that a difference in pH does not have a prominent effect on the SO_4 concentration in the stripping step of the experimental procedure.

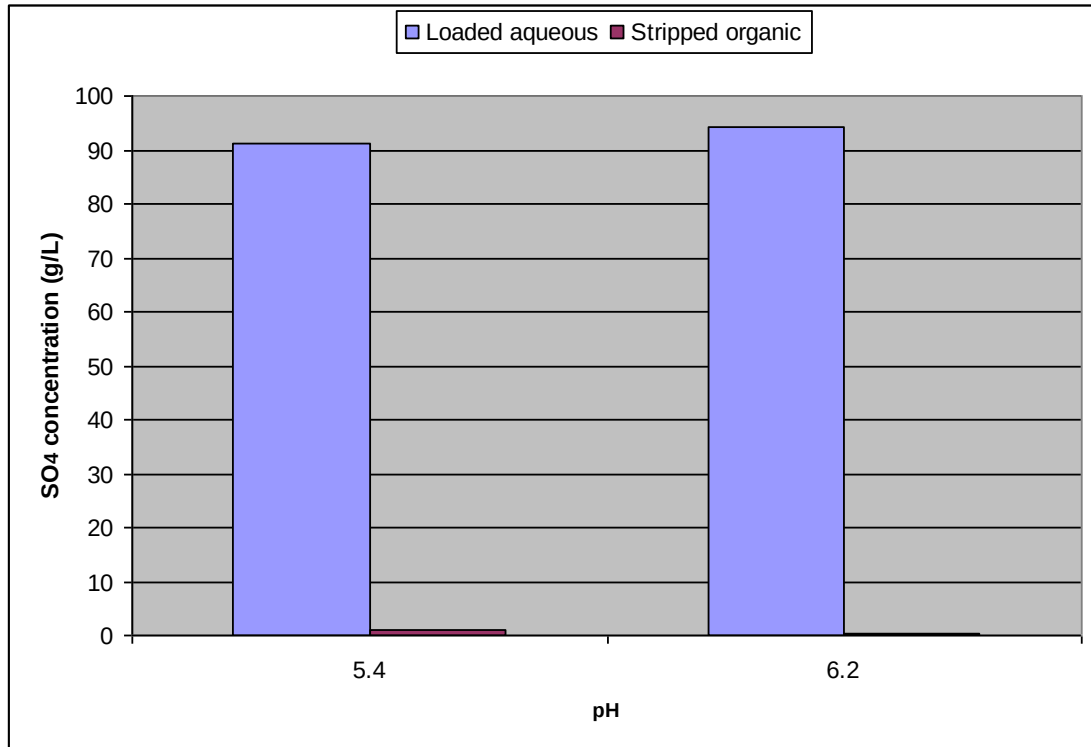


Figure F-1: pH effect on SO_4 concentration in the organic kerosene solution

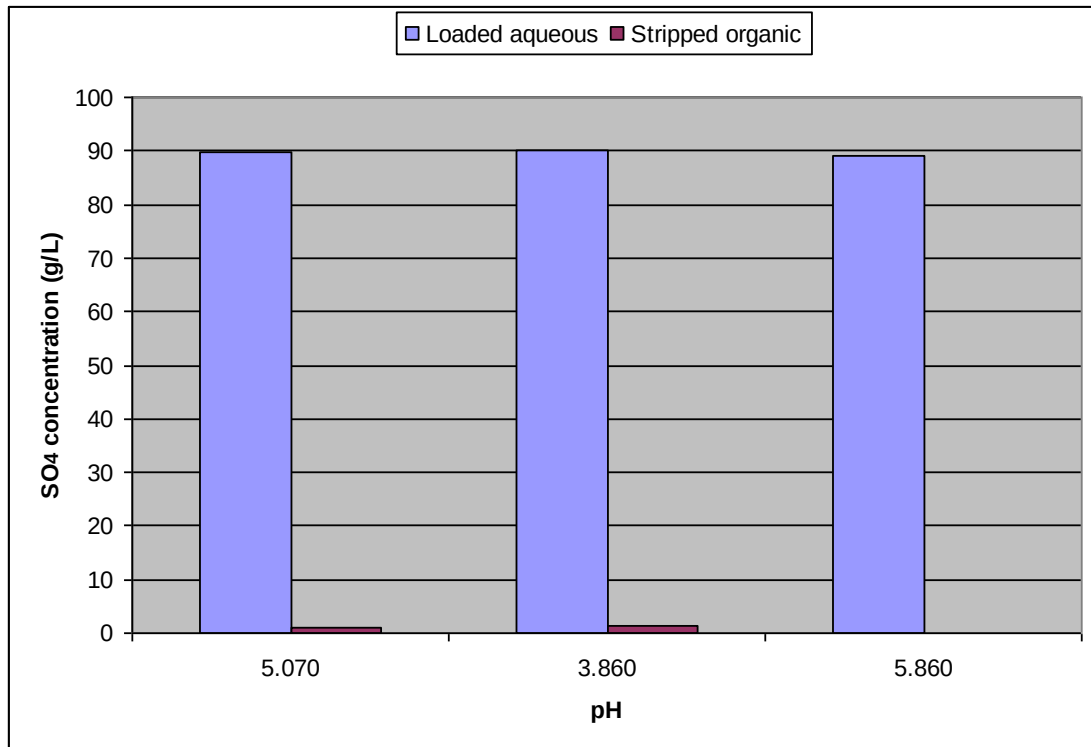


Figure F-2: pH effect on SO_4 concentration in the organic SSX 150 solution

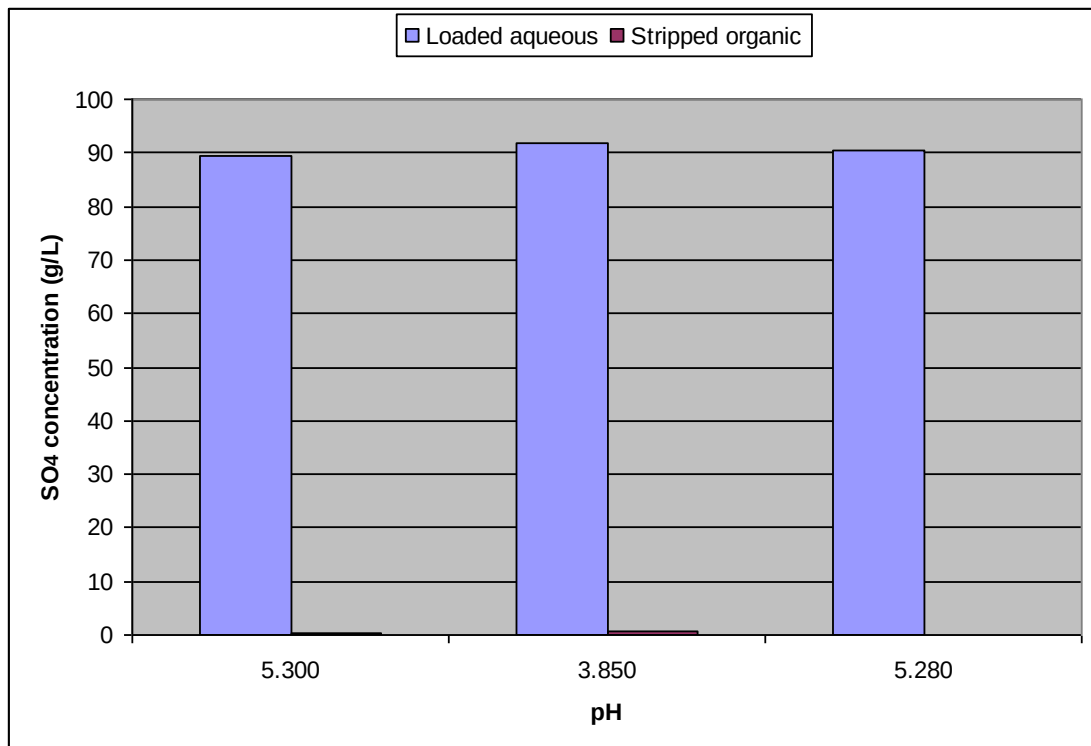


Figure F-3: pH effect on SO_4 concentration in the organic SSX 210 solution

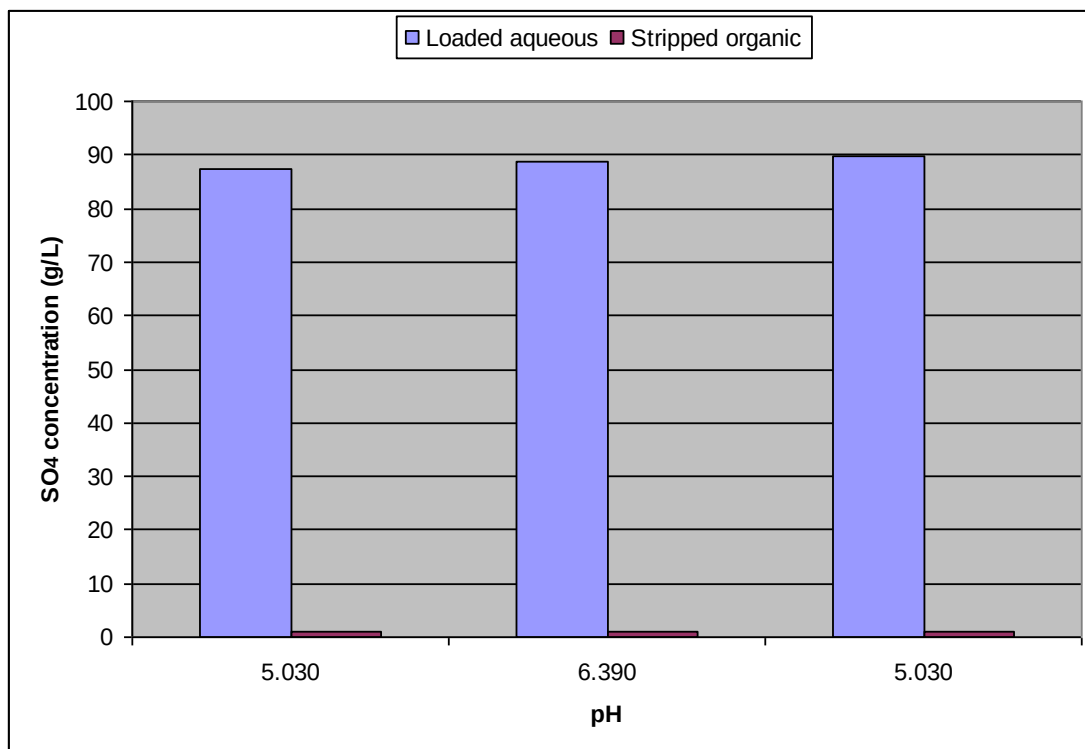


Figure F-4: pH effect on SO_4 concentration in the organic Biodiesel solution

Appendix G

Statistical report summary

The North-West University's Statistical Consultation Department evaluated the data from AngloGold Ashanti Vaal River Laboratories. The data were processed to produce graphs which were evaluated to obtain an overall reliability perspective of the data. Overall data reliability was found to be good, but inexplicable extreme outliers were identified. These outliers behaved outside the expected theoretical norm. Another evaluation made with the original data was to modify the extreme outliers to a theoretically predicted value. This data showed a very high consistency and is included to demonstrate how good the results are without outliers.

Statistical data evaluation

The figures and tables below were generated by a statistical consultant (Prof. Faans Steyn). The tables are not interpreted. They serve merely as a reference to be interpreted by a person with the necessary knowledge, should a further statistical evaluation be required.

Table G-1: Statistical parameters as evaluated from figure G-1 for U_3O_8

Effect	Univariate Tests of Significance, Effect Sizes, and Powers for Sulfate (Data_RvdR_oorspr.sta)							
	Sigma-restricted parameterization Effective hypothesis decomposition							
	SS	Degr. of Freedom	MS	F	p	Partial eta-squared	Non-centrality	Observed power (alpha=0.05)
Intercept	88131.2	1	88131.23	17144.75	0.000000	0.997788	17144.75	1.000000
Ekstraer middel	28.4	3	9.46	1.84	0.156273	0.126864	5.52	0.439388
"metode1"	103661.8	4	25915.45	5041.50	0.000000	0.998119	20166.01	1.000000
Ekstraer middel*"metode1"	55.5	12	4.62	0.90	0.555846	0.221161	10.79	0.423149
Error	195.3	38	5.14					

The numbers on the x-axis refer to the Transfer mechanism solutions.

Process step 1: Raffinate

Process step 2: Loaded organic

Process step 3: Scrub water

Process step 4: OK Liquor

Process step 5: Stripped organic

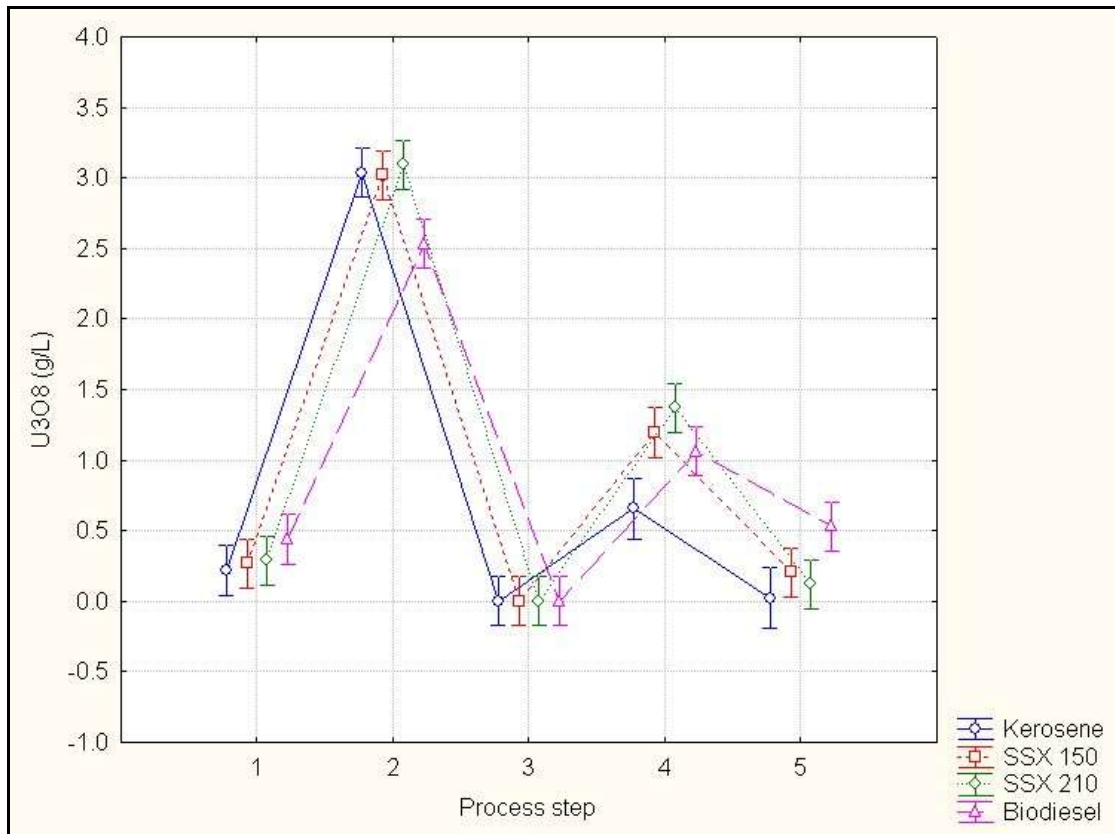


Figure G-1: Statistical plot of the U_3O_8 data analysis

It is apparent that the Kerosene, SSX 150 and SSX 210 behave similarly, and the experimental error is small enough to allow for the data to fall within each other's upper and lower confidence limits. The data point plotted for Kerosene at point 4 on the x-axis does not correlate with the known behaviour and the theoretical knowledge

of the diluent. Thus it was thought wise to include a second set of graphs, in which points identified as outliers were normalised. This modified data set and its results are included in the next section.

Table G-2: Statistical parameters as evaluated from figure G-2 for Sulfates

Effect	Univariate Tests of Significance, Effect Sizes, and Powers for Yster (Data_RvdR_oorspr.sta) Sigma-restricted parameterization Effective hypothesis decomposition Exclude condition: metode1=2 or metode1=5							
	SS	Degr. of Freedom	MS	F	p	Partial eta-squared	Non-centrality	Observed power (alpha=0.05)
Intercept	2.022114	1	2.022114	101.2486	0.000000	0.814887	101.2486	1.000000
Ekstraer middel	0.036162	3	0.012054	0.6036	0.619319	0.072979	1.8107	0.155676
"metode1"	4.016899	2	2.008450	100.5644	0.000000	0.897380	201.1289	1.000000
Ekstraer middel*"metode1"	0.078639	6	0.013107	0.6563	0.685062	0.146172	3.9375	0.209526
Error	0.459351	23	0.019972					

Table G-2 indicates the reliability of the data as charted on figure G-2. The statistical 95% confidence intervals for the sulfates are the smallest and indicate good data quality.

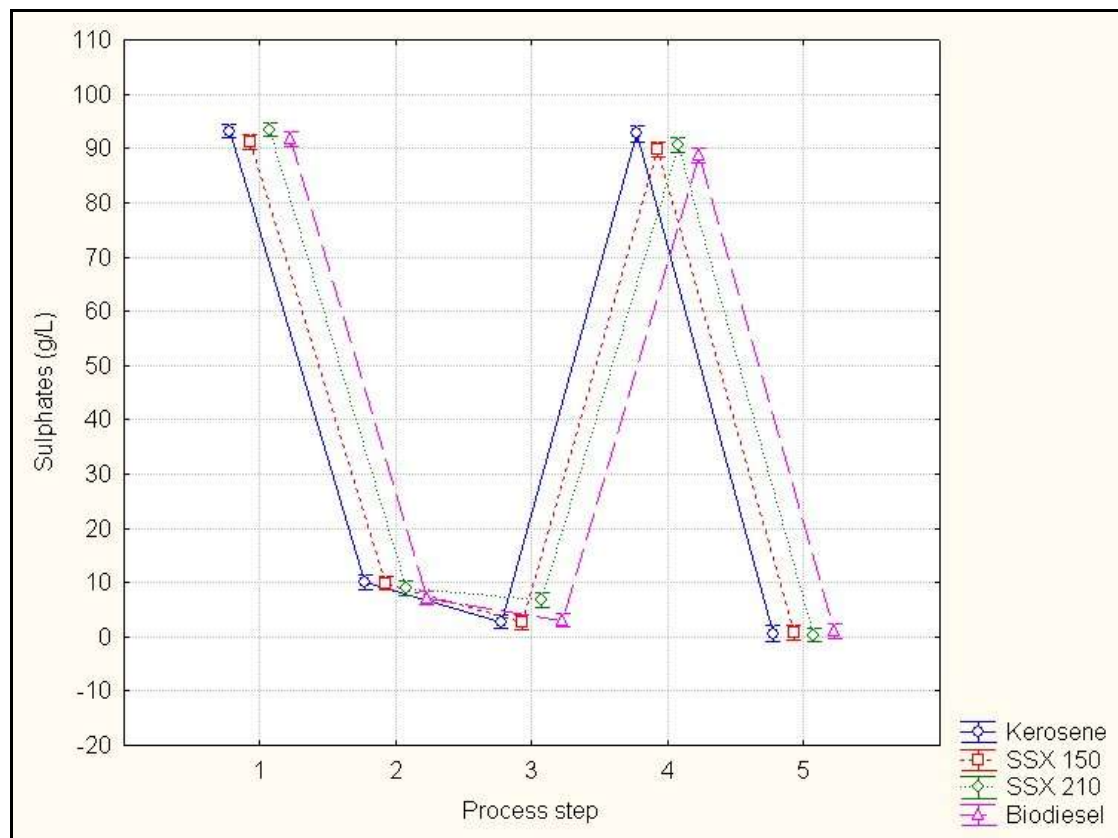


Figure G-2: Statistical plot of the SO₄ data analysis

Table G-3: Statistical parameters as evaluated from figure G-3 for Fe

Univariate Tests of Significance, Effect Sizes, and Powers for Yster (Data_RvdR_oorspr.sta) Sigma-restricted parameterization Effective hypothesis decomposition Exclude condition: metode1=2 or metode1=5								
Effect	SS	Degr. of Freedom	MS	F	p	Partial eta-squared	Non-centrality	Observed power (alpha=0.05)
Intercept	2.022114	1	2.022114	101.2486	0.000000	0.814887	101.2486	1.000000
Ekstraer middel	0.036162	3	0.012054	0.6036	0.619319	0.072979	1.8107	0.155676
"metode1"	4.016899	2	2.008450	100.5644	0.000000	0.897380	201.1289	1.000000
Ekstraer middel*"metode1"	0.078639	6	0.013107	0.6563	0.685062	0.146172	3.9375	0.209526
Error	0.459351	23	0.019972					

Table G-3 indicates the reliability of the data as charted on figure G-3.

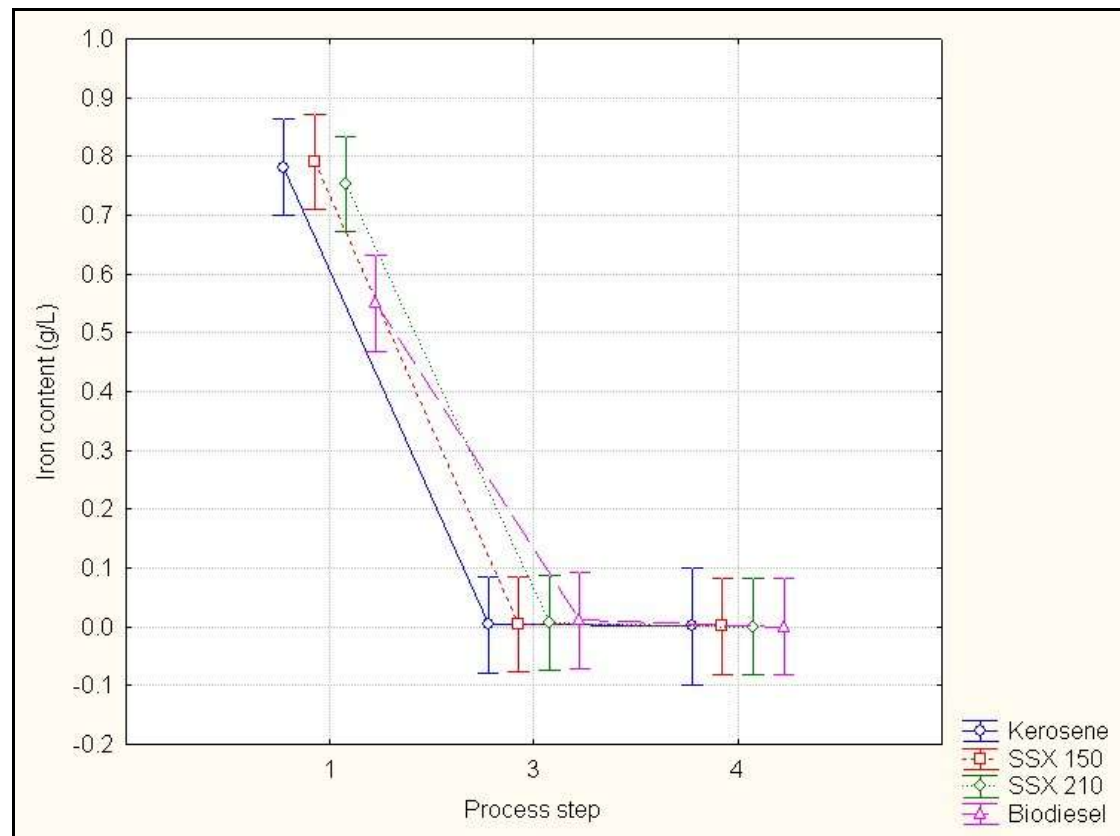


Figure G-3: Statistical plot of the Fe data analysis

Modified statistic data evaluation

In this section extreme outliers influencing data representation were normalised. Each experiment was triplicated, and in the case of one of the three data points influencing the mean value dramatically, that outlier value was normalised to produce a more acceptable data value. The extreme outliers were modified according to an expected theoretical number, that would correlate more with the expected result.

Table G-4: Statistical parameters as evaluated from figure G-4 for U_3O_8

Effect	Univariate Tests of Significance, Effect Sizes, and Powers for Sulfate (Data_RvdR_Aangepas.sta)							
	SS	Degr. of Freedom	MS	F	p	Partial eta-squared	Non-centrality	Observed power (alpha=0.05)
Intercept	88206.1	1	88206.05	88308.34	0.000000	0.999570	88308.3	1.000000
Ekstraer middel	7.7	3	2.55	2.55	0.069650	0.167848	7.7	0.584008
"metode1"	103714.6	4	25928.66	25958.73	0.000000	0.999634	103834.9	1.000000
Ekstraer middel*"metode1"	30.9	12	2.58	2.58	0.013025	0.449034	31.0	0.929944
Error	38.0	38	1.00					

The data normalisation leads to clearer data representation.

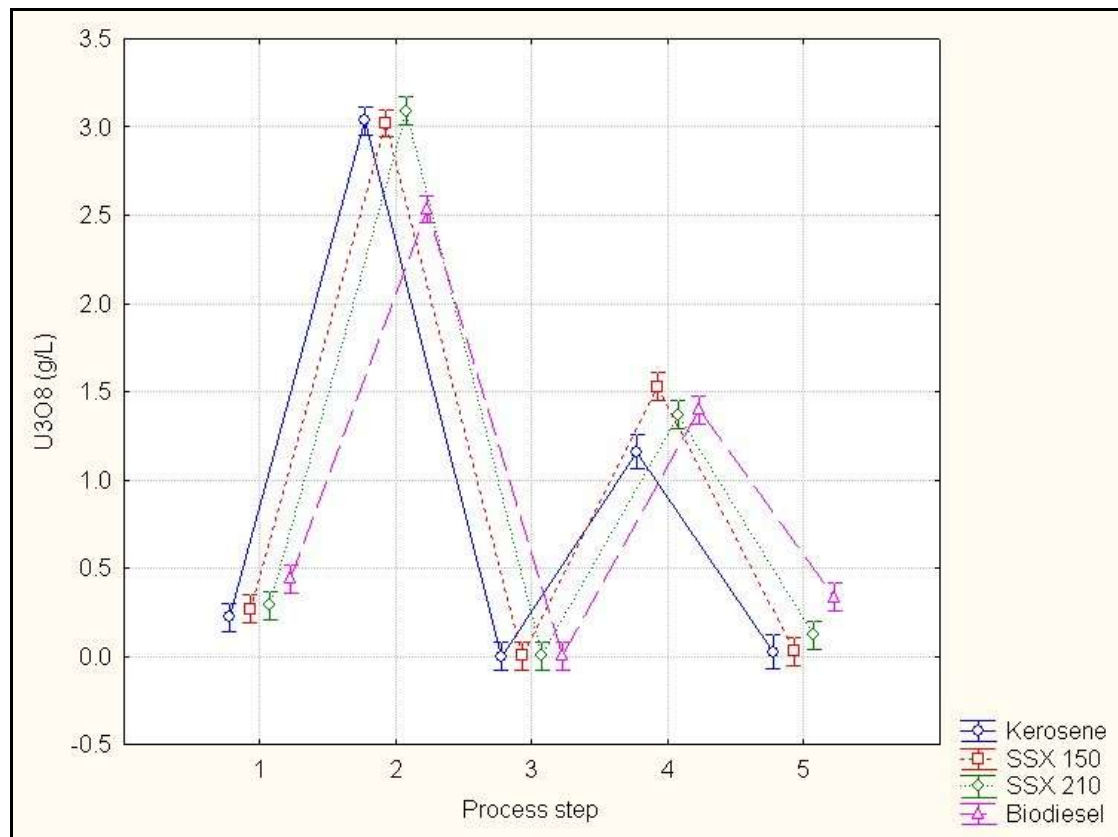


Figure G-4: Statistical plot of the modified U_3O_8 data analysis

Table G-5: Statistical parameters as evaluated from figure G-5 for Sulfates

Effect	Univariate Tests of Significance, Effect Sizes, and Powers for Yster (Data_RvdR_Aangepas.sta) Sigma-restricted parameterization Effective hypothesis decomposition Exclude condition: metode1=2 or metode1=5							
	SS	Degr. of Freedom	MS	F	p	Partial eta-squared	Non-centrality	Observed power (alpha=0.05)
Intercept	2.410722	1	2.410722	11199.82	0.000000	0.997951	11199.82	1.000000
Ekstraer middel	0.002397	3	0.000799	3.71	0.025900	0.326269	11.14	0.731736
"metode1"	4.800289	2	2.400144	11150.68	0.000000	0.998970	22301.37	1.000000
Ekstraer middel*"metode1"	0.004078	6	0.000680	3.16	0.020816	0.451649	18.94	0.829962
Error	0.004951	23	0.000215					

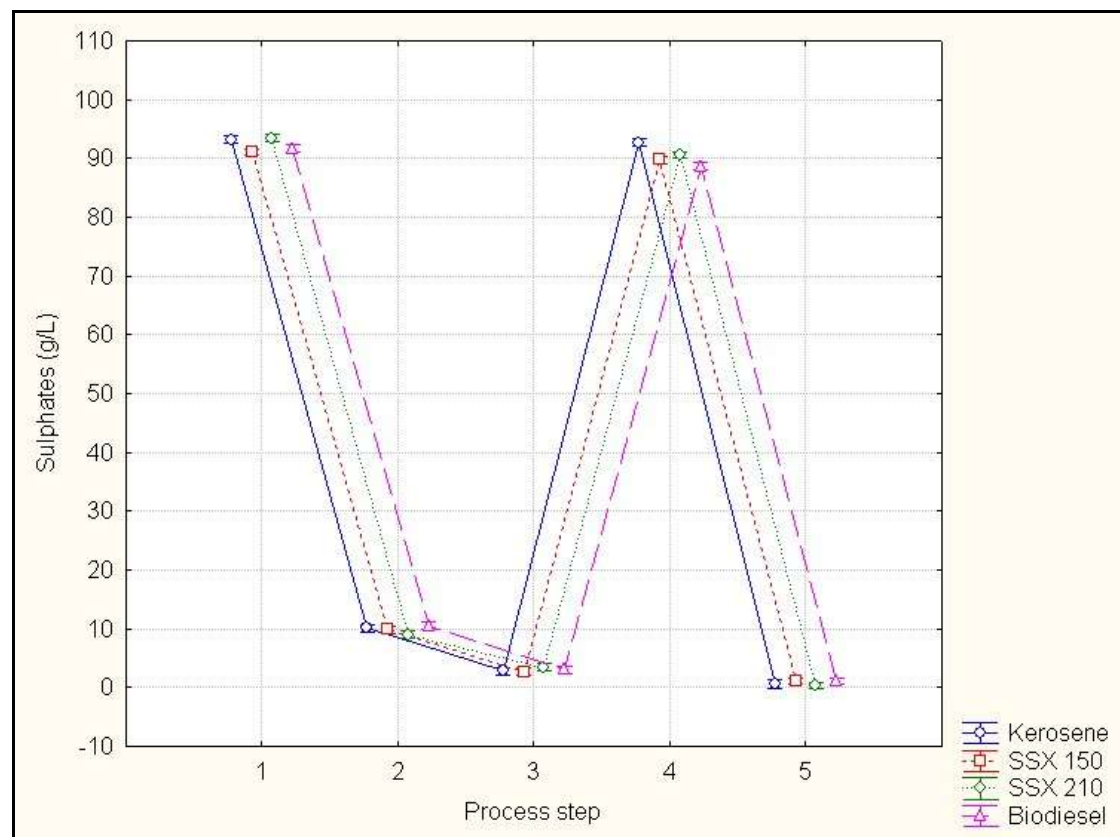
**Figure G-5: Statistical plot of the modified SO₄ data analysis**

Table G-6: Statistical parameters as evaluated from figure G-6 for Fe

Univariate Tests of Significance, Effect Sizes, and Powers for Yster (Data_RvdR_Aangepas.sta) Sigma-restricted parameterization Effective hypothesis decomposition Exclude condition: metode1=2 or metode1=5								
Effect	SS	Degr. of Freedom	MS	F	p	Partial eta-squared	Non-centrality	Observed power (alpha=0.05)
Intercept	2.410722	1	2.410722	11199.82	0.000000	0.997951	11199.82	1.000000
Ekstraer middel	0.002397	3	0.000799	3.71	0.025900	0.326269	11.14	0.731736
"metode1"	4.800289	2	2.400144	11150.68	0.000000	0.998970	22301.37	1.000000
Ekstraer middel*"metode1"	0.004078	6	0.000680	3.16	0.020816	0.451649	18.94	0.829962
Error	0.004951	23	0.000215					

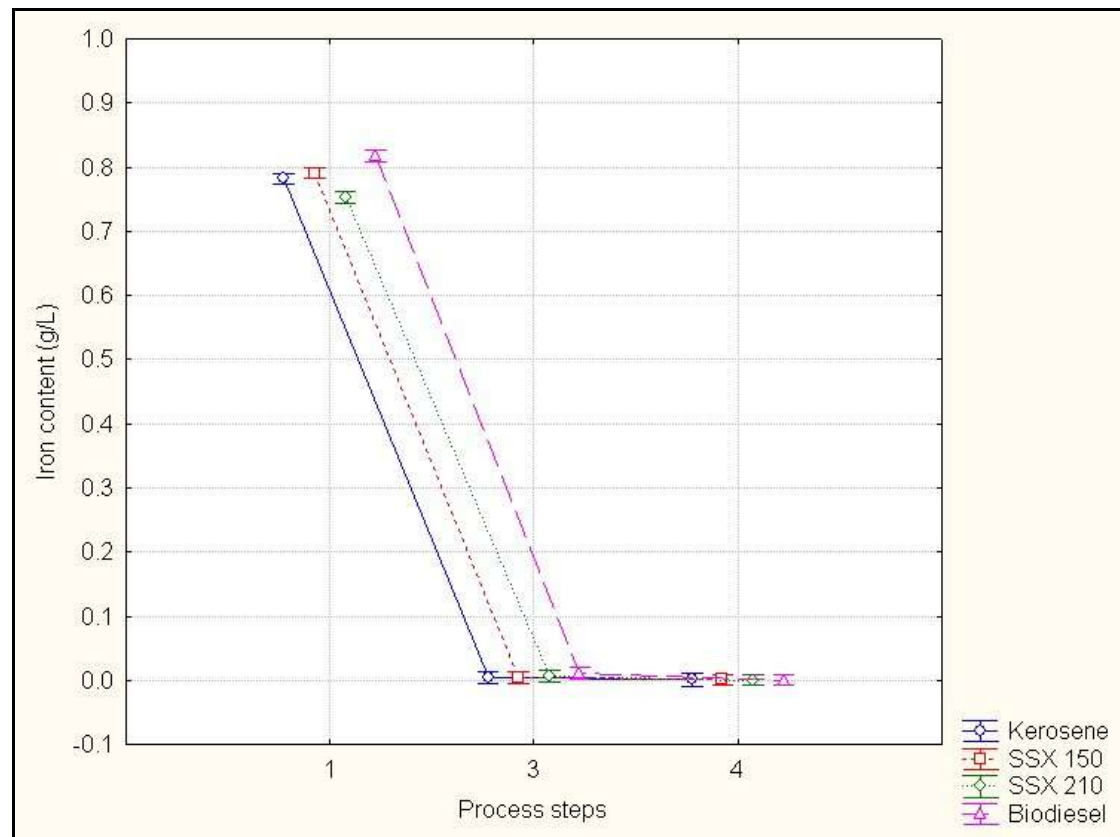


Figure G-6: Statistical plot of the modified Fe data analysis

**MATERIAL SAFETY DATA SHEET**

Revision Date : 27.05.2008

1. PRODUCT AND COMPANY IDENTIFICATION

Product name : ENGEN LAUREL PARAFFIN
Chemical name : Kerosene
Synonyms : Paraffin
Product use : General purpose fuel
UN number : 1223

Supplier : Engen Petroleum Limited (Tel: 021-403 4911, a/h: 021-403 4099)
Health Emergency Telephone : 021-689 5227 (Red Cross Poison Service)
Transport Emergency Telephone : 011-975 1278/83 (Hazchemwise)
Customer Service Center : 0860 036 436 (Sales and Technical Information)
MSDS Internet website : www.engen.co.za/content/products/default2.htm

2. COMPOSITION/INFORMATION ON INGREDIENTS

Chemical name	CAS-No.	Weight%	Symbol Codes	R-Phrase Numbers
Kerosene	8008-20-6	> 98.00	Xn, N	R10, R38, R67, R65, R51/53
Ethyl Benzene	100-41-4	< 1.00	Xn	R20, R45
Naphthalene	91-20-3	< 1.00		R45

See Section 15 for European Label Information.

See Section 8 for Exposure Limits (if applicable).

3. HAZARDS IDENTIFICATION

Emergency response data : Colourless Liquid. Flammable. Product can accumulate a static charge and release vapours which may cause a fire or explosion. DOT ERG No. : 128

Potential health effects

Inhalation : Respiratory irritation, dizziness, nausea and loss of consciousness.

Skin : Prolonged repeated skin contact with low viscosity materials may defat the skin resulting in possible irritation and dermatitis.

Eye : Practically non-irritating.

Ingestion : Practically non-toxic, but when swallowed can cause lung damage.

Potential environmental effects : Toxic to fish, aquatic organisms and wildlife. Do not discharge into lakes, streams, ponds and ground water supply.

See Section 11 for further health effects/toxicological data.

4. FIRST AID MEASURES

Inhalation : Remove from further exposure. If respiratory irritation, dizziness, nausea, or unconsciousness occurs, seek immediate medical assistance. If breathing has stopped, assist ventilation with mechanical device or use mouth-to-mouth resuscitation with a mouthpiece.

Skin contact : Remove contaminated clothing. Dry wipe exposed skin and cleanse with

ENGEN LAUREL PARAFFIN

hand cleaner, soap and water. Launder contaminated clothing before reuse. (See Section 16 - Injection Injury)

Eye contact	:	Flush thoroughly with water. If irritation occurs call a doctor.
Ingestion	:	Seek immediate medical attention. Do not induce vomiting.
Note to doctors	:	Material if aspirated into the lungs may cause chemical pneumonitis. Skin contact may aggravate an existing dermatitis. Treat appropriately.

5. FIRE-FIGHTING MEASURES

Extinguishing media	:	Carbon dioxide, foam, dry chemical and water fog.
Special fire fighting procedure	:	Water spray should only be used to keep fire-exposed containers cool, flush spills away from exposures, disperse vapours and protect personnel attempting to stop leak. Prevent runoff from fire control or dilution from entering streams, municipal sewers, or drinking water supply.
Special protective equipment for firefighters	:	For fires in enclosed areas, fire fighters must use Self-Contained Breathing Apparatus.
Unusual fire and explosive hazards	:	Flammable.
Products of decomposition	:	Fumes, smoke and carbon monoxide.
Flash Point	:	> 46 °C (ASTM D-56)
Upper Explosion Limit (UEL)	:	5.0 %(V)
Lower Explosion Limit (LEL)	:	0.7 %(V)
NFPA Hazard Id	:	Health: 0; Flammability: 2; Reactivity: 0

6. ACCIDENTAL RELEASE MEASURES

Procedure if material is released or spilled	:	Report spills/releases as required to appropriate authorities.
Methods for cleaning up	:	Absorb on fire retardant treated sawdust, diatomaceous earth, etc. Shovel up for later approved disposal. LARGE SPILLS: Contain material and pump back to holding tank for disposal or recycling in accordance with product characteristics and applicable regulations.
Personal precautions	:	See Section 8.
Environmental precautions	:	Prevent spills from entering municipal sewers or drains and contact with soil.

7. HANDLING AND STORAGE

Safe handling advice	:	Harmful in contact with or if absorbed through the skin. Avoid inhalation of vapours or mists. Use in well ventilated area away from all ignition sources.
Storage information	:	Store in a cool area. Small containers of approved design, properly sealed and labeled, should be stored in well ventilated surroundings and kept out of reach of children.
Storage and handling procedures	:	To minimize the risk of fire or explosion from discharges, static and/or vapour accumulation, effectively bond and ground product storage and transfer systems. Electrical equipment and fittings must comply with local fire prevention regulations for this class of product. Refer to national or local regulations covering safety at petroleum handling and storage areas for this product.

8. EXPOSURE CONTROLS / PERSONAL PROTECTION

Occupational Exposure Limits (OELs)

ENGEN LAUREL PARAFFIN

Components	CAS-No.	Source	TWA	Value		Notations
Kerosene	8008-20-6	ACGIH	LTEL	200 mg/m ³	50 ppm	Skin; A3
Ethyl Benzene	100-41-4	ACGIH TLV OSHA PEL	LTEL STEL LTEL STEL	434 mg/m ³ 543 mg/m ³ 435 mg/m ³ 545 mg/m ³	100 ppm 125 ppm 100 ppm 125 ppm	A3; BEI
Naphthalene	91-20-3	ACGIH TLV OSHA PEL	LTEL STEL LTEL STEL	52 mg/m ³ 79 mg/m ³ 50 mg/m ³ 75 mg/m ³	10 ppm 15 ppm 10 ppm 15 ppm	Skin; A4

LTEL: Long Term Exposure Limits - Time Weight Average (TWA) over 8 hours.

STEL: Short Term Exposure Limits - Time Weight Average (TWA) over 15 Minutes

Note: Limits Shown for guidance only. Follow applicable regulations.

Personal Protection Equipment (PPE)

Engineering controls	:	Use in well ventilated area. Explosive-proof ventilation equipment with local exhaust is desirable.
Respiratory protection	:	Approved respiratory equipment must be used when airborne concentrations are unknown or exceed the recommended exposure limit. Self-Contained Breathing Apparatus may be required for use in confined or enclosed spaces.
Eye protection	:	If splash with liquid is possible, chemical type goggles should be worn.
Skin and body protection	:	Impervious gloves must be worn. If body contact is likely, appropriate personal protective equipment must be worn. Good personal hygiene practices should always be followed.

9. PHYSICAL AND CHEMICAL PROPERTIES

Appearance	:	Liquid.
Colour	:	Colourless
Odour	:	Mild
Solubility	:	Negligible
Boiling point	:	> 140 °C
Flash Point	:	> 46 °C (ASTM D-56)
Upper Explosion Limit (UEL)	:	5.0 %(V)
Lower Explosion Limit (LEL)	:	0.7 %(V)
Vapour pressure	:	< 1.0 hPa
Density	:	0.79 g/cm ³ @ (ASTM D-4052)
Viscosity, kinematic	:	1.5 mm ² /s @ 40 °C (ASTM D-445)

10. STABILITY AND REACTIVITY

Stability	:	Stable.
Conditions to avoid	:	Heat, sparks, flame and build up of static electricity.
Materials to avoid	:	Strong oxidizers.
Hazardous decomposition products	:	Fumes, smoke and carbon monoxide.

11. TOXICOLOGICAL INFORMATION

Acute oral toxicity	:	(Rats): Practically non-toxic (LD50: Greater than 2000 mg/kg). Based on testing of similar products and/or components.
Acute inhalation toxicity	:	(Rats): Practically non-toxic (LC50: greater than 5mg/l). Based on

ENGEN LAUREL PARAFFIN

testing of similar products and/or the components.

Acute dermal toxicity	:	(Rabbits): Practically non-toxic (LD50: greater than 2000 mg/kg). Based on testing of similar products and/or the components.
Skin irritation	:	(Rabbits): Irritant. (Primary Irritation Index: greater than 3 but less than 6). Based on testing of similar products and/or the components.
Eye irritation	:	(Rabbits): Practically non-irritating. (Draize score: greater than 6 but 15 or less). Based on testing of similar products and/or the components.
Repeated dose toxicity	:	Certain straight-run middle distillates have been found to produce skin tumors in laboratory mouse skin-painting tests, but these have usually been associated with a high level of skin irritation. Laboratory tests have indicated that the irritation can produce tumours. Therefore, if the precautions outlined in this MSDS are followed to minimize repeated or prolonged skin contact which could cause irritation, these oils should pose no carcinogenic hazard to humans.
Teratogenicity	:	A review of the literature indicates that inhalation of kerosene vapours does not cause reproductive or developmental effects in laboratory animals. There is no evidence of effects on humans.
Other toxicological information	:	This product contains ethylbenzene. The International Agency for Research on Cancer (IARC) has evaluated ethylbenzene and classified it as possibly carcinogenic to humans (Group 2B) based on sufficient evidence for carcinogenicity in experimental animals, but inadequate evidence for cancer in exposed humans.

12. ECOLOGICAL INFORMATION

Elimination information (persistence and degradability)

Biodegradability	:	The majority of the components in this product would be expected to be inherently biodegradable. The constituents of kerosene which are volatilized will photodegrade in the atmosphere. The less volatile, more water-soluble components which are aromatic hydrocarbons will also undergo aqueous photodegradation.
Physico-chemical removability	:	Not established.
Bioaccumulation	:	Not established.

Ecotoxicity effects

Toxicity to fish	:	(Rainbow trout) LC/EC50: 18 - 25 mg/l at 96 hours.
Toxicity to aquatic organisms	:	(Daphnia) Immobilisation (50%): 1.4 - 21 mg/l at 48 hours. (Algae) Growth Inhibition (50%): 4 - 15 mg/l at 72 hours.

Further information on ecology

Remarks	:	This environmental assessment is based on test data for this product (or estimated data).
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13. DISPOSAL CONSIDERATIONS

Waste disposal	:	Product is suitable for burning for fuel value compliance with applicable laws and regulations.
Contaminated packaging	:	Empty containers retain residue (liquid and/or vapour) and can be dangerous. DO NOT PRESSURIZE, CUT, WELD, BRAZE, SOLDER, DRILL, GRIND OR EXPOSE SUCH CONTAINERS TO HEAT, FLAME, SPARKS, STATIC ELECTRICITY, OR OTHER SOURCES OF IGNITION; THEY MAY EXPLODE AND CAUSE INJURY OR DEATH. Do not attempt to refill or clean container since residue is difficult to remove. Empty drums should be completely drained, properly bunged and promptly returned to a drum reconditioner. All containers should be disposed of in an environmentally

ENGEN LAUREL PARAFFIN

safe manner and in accordance with governmental regulations.

Other regulations	:	Disposal of unused product may be subject to RCRA regulations (40 CFR 261). Disposal of the used product may also be regulated due to ignitability, corrosivity, reactivity, or toxicity as determined by the Toxicity Characteristic Leaching Procedure (TCLP).
Flash Point	:	> 46 °C (ASTM D-56)

14. TRANSPORT INFORMATION

Note	:	The flash point of this material is > 38 °C, and hence regulatory classifications for flammability may vary.
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ADR

Proper shipping name	:	KEROSENE
UN number	:	1223
Class	:	3
Letter	:	F
Packing group	:	III
Labelling number	:	3

CFR

Proper shipping name	:	KEROSENE
UN number	:	1223
Class	:	3
Letter	:	F
Packing group	:	III
Labelling number	:	3

IATA_C

Proper shipping name	:	KEROSENE
UN number	:	1223
Class	:	3
Letter	:	F
Packing group	:	III
Labelling number	:	3

IMDG

Proper shipping name	:	KEROSENE
UN number	:	1223
Class	:	3
Letter	:	F
Packing group	:	III
Labelling number	:	3
Marine pollutant	:	Marine pollutant
Medical First Aid Guide (MFAG) table	:	311
Emergency Schedule (EmS) number	:	3-07
IMDG code page number	:	3375
Static Accumulator (50 picosiemens or less)	:	Yes

15. REGULATORY INFORMATION

US OSHA Hazard Communication Standard	:	Product assessed in accordance with OSHA 29 CFR 1910.1200 and determined to be hazardous.
Governmental Inventory Status	:	All components comply with TSCA, EINECS/ELINCS, AICS, METI, DSL, KECI, ENCS, PICCS and IECSC.
EU Labelling	:	Product is dangerous as defined by the European Union Dangerous Substances/Preparations Directives.
Symbols	:	Xn, N Harmful, Dangerous for the environment

ENGEN LAUREL PARAFFIN

R-Phrase(s)	:	R10, R38, R67, R65, R51/53 Flammable., Irritating to skin., Vapours may cause drowsiness and dizziness., Harmful: may cause lung damage if swallowed., Toxic to aquatic organisms, may cause long-term adverse effects in the aquatic environment.
S-phrase(s)	:	S2, S16, S43, S24, S62 Keep out of the reach of children., Keep away from sources of ignition - No smoking., In case of fire use foam/drypowder/carbon dioxide., Avoid contact with the skin., If swallowed, do not induce vomiting: seek medical advice immediately and show this container or label.
Note	:	Contains straight-run Kerosene.

SARA

U.S. Superfund Amendments and Reauthorization Act SARA Title III	:	This product contains no "EXTREMELY HAZARDOUS SUBSTANCES".
SARA (311/312) Reportable Hazard Categories	:	Fire Chronic Acute
SARA (313) Toxic Release Chemicals:	:	This product contains no chemicals reportable under SARA (313) Toxic Release Chemicals:

The following product ingredients are cited on the lists below

Chemical name	CAS-No.	Concentration [%]	List Citations
Kerosene	8008-20-6	> 98.00	19, 21, 25, 26
Ethyl Benzene	100-41-4	< 1.00	1, 8, 10, 18, 19, 20, 21, 23, 24, 25, 26
Naphthalene	91-20-3	< 1.00	16, 22

Regulatory List Searched

1 = ACGIH ALL	6 = IARC 1	11 = TSCA 4	17 = CA P65	22 = MI 293
2 = ACGIH A1	7 = IARC 2A	12 = TSCA 5a2	18 = CA RTK	23 = MN RTK
3 = ACGIH A2	8 = IARC 2B	13 = TSCA 5e	19 = FL RTK	24 = NJ RTK
4 = NTP CARC	9 = OSHA CARC	14 = TSCA 6	20 = IL RTK	25 = PA RTK
5 = NTP SUS	10 = OSHA Z	15 = TSCA 12b	21 = LA RTK	26 = RI RTK

Code Key: CARC = Carcinogen; SUS = Suspected Carcinogen

16. OTHER INFORMATION

Note: Engen products do not contain PCBs.

Health studies have shown that many hydrocarbons pose potential human health risks which may vary from person to person. Information provided on this MSDS reflects intended use. This product should not be used for any other applications. In any case, the following advice should be considered:

INJECTION INJURY WARNING: If product is injected into or under the skin, or into any part of the body, regardless of the appearance of the wound or its size, the individual should be evaluated immediately by a doctor as a surgical emergency. Even though initial symptoms from high pressure injection may be minimal or absent, early surgical treatment within the first few hours may significantly reduce the ultimate extent of injury.

Precautionary Label Text:

CONTAINS KEROSENE

CAUTION!

COMBUSTIBLE LIQUID AND VAPOUR. CAUSES SKIN IRRITATION. MAY CAUSE NOSE, THROAT AND LUNG IRRITATION, DIZZINESS, NAUSEA, LOSS OF CONSCIOUSNESS. LOW VISCOSITY MATERIAL - IF SWALLOWED, MAY BE ASPIRATED AND CAN CAUSE SERIOUS OR FATAL LUNG DAMAGE.

SAFETY: Keep away from heat, sparks, and flame. Keep container closed. Use with adequate ventilation.

ENGEN LAUREL PARAFFIN

Avoid breathing mist or vapour. Avoid prolonged or repeated skin contact.

FIRST AID: In case of contact, wash skin with soap and water. Remove contaminated clothing. Destroy or wash clothing before reuse. If swallowed, seek immediate medical attention. Do not induce vomiting. Only induce vomiting at the instruction of a doctor.

For industrial use only. Not intended or suitable for use in or around a household or dwelling.

This warning is given to comply with California Health and Safety Code 25249.6 and does not constitute an admission or a waiver of rights. This product contains a chemical known to the State of California to cause cancer, birth defects, or other reproductive harm. Chemicals known to the State of California to cause cancer, birth defects, or other reproductive harm are created by the combustion of this product. Refer to product Material Safety Data Sheet for further safety and health information.

Disclaimer

Information given herein is offered in good faith as accurate, but without guarantee. Conditions of use and suitability of the product for particular uses are beyond our control; all risks of use of the product are therefore assumed by the user and we expressly disclaim all warranties of every kind and nature, including warranties of merchantability and fitness for a particular purpose in respect to the use or suitability of the product. Nothing is intended as a recommendation for uses which infringe valid patents or as extending license under valid patents. Appropriate warnings and safe handling procedures should be provided to handlers and users.

Prepared by	:	Product Safety Adviser Health, Safety, Environment and Quality Department Engen Petroleum Limited P.O.Box 35, Cape Town, 8000
Telephone	:	(021) 403 4805 / 4911 (Office Hours) (021) 403 4099 (After Hours) 083 628 4415 (Cellular)



EECO fuels

B100 biodiesel batch test result

Batch # 579
Date Tested 13/10/08

Test	Units	ASTM 6751-03	EN 14214	Batch 1	Remarks
Flash point	C	130	120	180	Pass
Sediment	%v/v	0.05	0.05	0.05	Pass
Water	%m/m	0.05	0.05	0.02	Pass
Kinematic Viscosity	cST	6	5	7.1	Pass
Sulphated Ash	%m/m	0.02	0.02	0.005	Pass
Total Sulphur	mg/l (ppm)	500	10	109	RSA Diesel @ 300 ppm
Copper Corrosion		3	1	1	Pass
Cloud Point	C			5	Country specific
Carbon Residue	%m/m	0.5	0.3	0.4	Pass
Total Acid Number	mgKOH/g	0.8	0.5	0.49	Pass
Total Glycerine	%m/m	0.24	0.25	0.01	Pass
Phosphorus as P	mg/l (ppm)	10	10	6	Pass

Flash point

PASS

The Biodiesel flashpoint is indicative of the quantity of methanol present in the Biodiesel. The higher the flashpoint the lower the quantity of residual methanol present in the Biodiesel.

Residual methanol affects fuel pumps, seals and elastomers and can result in poor combustion properties

Water

PASS

Water content is indicative of the quantity of water present in the Biodiesel

Excess water can lead to corrosion, piston crown damage and provides an environment for algae growth.

Sediment

PASS

Sediment content is indicative of the quantity of impurities present in the Biodiesel

High sediment levels are indicative of poor filtration and fuel oxidation

**Kinematic
Viscosity**

PASS

Biodiesel viscosity is a measure of the thickness of the biodiesel. The viscosity of the biodiesel is a function of the feedstock oil.

High viscosity fuels can cause poor fuel combustion, leading to deposit formation and elevated engine oil dilution

Sulphated Ash

PASS

Sulphated ash indicates the amount of residual alkali catalyst present in the biodiesel as well as any other ash forming compounds present.

Ash compounds contribute to injector deposits and fuel system fouling

Sulphur

PASS

Sulphur limits are imposed to reduce sulphate and sulphuric acid pollutants and protect future exhaust system catalytic converters.

Biodiesel sulphur limits are set to meet those required to be met by petrodiesel and as such a value of less than 500 ppm is required to meet the South African Standard

Copper Corrosion

PASS

A copper corrosion test is conducted to indicate potential difficulties with copper and bronze fuel systems. While copper and bronze may not corrode in the presence of biodiesel fuel, prolonged contact with these catalysts can cause fuel degradation and sediment formation.

Cloud point

PASS

Cloud point is a measure of the temperature at which the biodiesel begins to gel.

Carbon Residue

PASS

Carbon residue gives a measure of the carbon depositing tendency of a fuel and is an approximation of the tendency for carbon deposits to form in an engine.

Acid Number

PASS

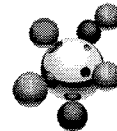
The acid number is indicative of free fatty acids. A high acid number is indicative of a poor reaction process or oxidative degradation. Fuels with acid numbers in excess of 0.8 cause fuel system deposits and reduce fuel pump and filter lifespan.

Total Glycerine**PASS**

Total Glycerine numbers measure the amount of unconverted or partially converted fats and by-product glycerine present in the fuel. A high total glycerine number is indicative of incomplete conversion of the feedstock fats and oils into biodiesel or incomplete removal of glycerine.

Phosphorus**PASS**

Phosphorus levels are limited to below 10 ppm to prevent damage to catalytic converters.



product data sheet

SSX™150

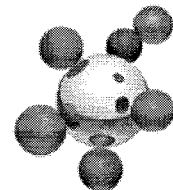
Code 1994 Revision 2 1 July 2003

Properties	Test method	Units	Specification	Typical values
Aromatics	ASTM D 1840	mass %	0.3 max	<0.1
Sulphur	Sasol 1.260	mg/kg	5 max	<1
Density @ 20°C	Sasol 1.173	kg/l	Report	0.7285
Colour	Sasol 1.31	Saybolt	+25 min	+30
Kinematic viscosity@ 40°C	ASTM D 445	cSt	Report	1.19
Flash point (closed cup)	ASTM D 93	°C	40 min	45
Distillation	ASTM D 86	°C		
Initial boiling point			150 min	155
Dry point			205 max	195
Bromine Index	ASTM D 2710	mg Br/100g	15 max	<10
Copper corrosion	ASTM D 130		Report	1a

Packaging

SSX™150 is available in bulk or in 210 litre drums.

Notice *This product information is indicative and does not include any guarantee*



Material Safety Data Sheet

SSX 150

1 Chemical product and company identification

Common name	: SSX 150	Code	: 1994
Supplier	: Sasol Wax P.O. Box 1 Sasolburg 1947 Republic of South Africa TEL: +27 16 960 3002	MSDS#	:
Synonym	: Hydrocarbon blend, normal alkanes	Validation date	: 11/21/2003.
Trade name	: SSX 150	Print date	: 11/21/2003.
Material uses	: Mining industry: Diluent for metal extraction in the mining industry.	Prepared by	: Aneshia Ambaram
Manufacturer	: Sasol Chemical Industries P.O. Box 1 Sasolburg 1947 Republic of South Africa TEL: +27 16 960-9111	In case of emergency	: SOUTH AFRICA: 0800 11 28 90 INTERNATIONAL: +27 17 610 4444

2 Composition / information on ingredients

Name	CAS #	% by weight	Exposure limits
May contain: Nonane	111-84-2	30-50	ACGIH TLV (United States, 2003) TWA: 200 ppm 8 hour(s). AIHA WEEL (United States) TWA: 45 ppm 8 hour(s). TWA: 250 mg/m ³ 8 hour(s).
Decane	124-18-5	30-50	
Iso-paraffins		0-10	

3 Hazards identification

Physical state and appearance	: Clear liquid.
Emergency overview	: WARNING! FLAMMABLE LIQUID AND VAPOR. VAPOR MAY CAUSE FLASH FIRE. HARMFUL, MAY CAUSE LUNG DAMAGE IF SWALLOWED. VAPORS MAY CAUSE DROWSINESS AND DIZZINESS. REPEATED EXPOSURE MAY CAUSE SKIN DRYNESS AND CRACKING. TOXIC TO AQUATIC ORGANISMS, MAY CAUSE LONG-TERM ADVERSE EFFECTS. Keep away from heat, sparks and flame. Keep container closed. Use only with adequate ventilation. If swallowed, seek medical advice immediately and show this container or label.
Routes of entry	: Absorbed through skin. Eye contact. Inhalation. Ingestion.
Potential acute health effects	
Eyes	: Hazardous in case of eye contact.
Skin	: Repeated exposure may cause skin dryness or cracking.
Inhalation	: Vapors may cause drowsiness and dizziness.

Ingestion : Harmful if swallowed. Aspiration hazard if swallowed- can enter lungs and cause damage.

Potential chronic health effects : **CARCINOGENIC EFFECTS** Not listed.
MUTAGENIC EFFECTS Not listed.
TERATOGENIC EFFECTS Not listed.

Medical conditions aggravated by overexposure: : Repeated or prolonged exposure is not known to aggravate medical condition.

Overexposure /signs/symptoms : Inhalation of vapour can produce headache, drowsiness, dizziness, anaesthetic effect and central nervous system depression, which can lead to loss of coordination, numbness, impaired judgement, inability to concentrate and, if exposure is prolonged, unconsciousness.

See toxicological information (section 11)

4 First aid measures

Eye contact : Check for and remove any contact lenses. In case of contact, immediately flush eyes with plenty of water for at least 15 minutes. Get medical attention.

Skin contact : In case of contact, immediately flush skin with plenty of water. Remove contaminated clothing and shoes. Wash clothing before reuse. Thoroughly clean shoes before reuse. Get medical attention.

Inhalation : If inhaled, remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. Get medical attention.

Ingestion : Do NOT induce vomiting unless directed to do so by medical personnel. Never give anything by mouth to an unconscious person. Loosen tight clothing such as a collar, tie, belt or waistband. If large quantities of this material are swallowed, call a physician immediately.

Notes to physician : Support respiratory and cardiovascular function.

5 Fire fighting measures

Flammability of the product : Flammable.

Autoignition temperature : No data available.

Flash points : Closed cup: 42°C (107.6°F).

Flammable limits : No data available.

Products of combustion : These are carbon oxides (CO, CO₂).

Fire hazards in presence of various substances : Flammable in presence of open flames, sparks, static discharge and oxidizing materials.

Explosion hazards in presence of various substances : Acids, alkalis and strong oxidisers.

Fire fighting media and instructions : SMALL FIRE: Use DRY chemical powder.
LARGE FIRE: Use water spray, fog or foam. Do not use water jet.

Protective clothing (fire) : Be sure to use an approved/certified respirator or equivalent.

Special remarks on fire hazards : No additional remark.

Special remarks on explosion hazards : No additional remark.

6 Accidental release measures

Small spill and leak : Absorb with an inert material and put the spilled material in an appropriate waste disposal.

Large spill and leak : Keep away from heat. Keep away from sources of ignition. Stop leak if without risk. Avoid inhalation of vapours. Prevent run off into drains and waterways. Use absorbent (soil, sand or other inert material).

7 Handling and storage

- Handling** : Keep away from heat, sparks and flame. Keep container closed. Use only with adequate ventilation. To avoid fire, minimize ignition sources. Do not ingest.
- Storage** : Keep container in a cool, well-ventilated area. Keep container tightly closed and sealed until ready for use. Avoid all possible sources of ignition (spark or flame).

8 Exposure controls, personal protection

- Engineering controls** : Provide exhaust ventilation or other engineering controls to keep the airborne concentrations of vapors below their respective occupational exposure limits. Ensure that eyewash stations and safety showers are proximal to the work-station location.

Personal protection

- Eyes** : Splash goggles.
- Body** : Chemical resistant protective suit.
- Respiratory** : Vapor respirator. Be sure to use an approved/certified respirator or equivalent. Wear appropriate respirator when ventilation is inadequate.
- Hands** : Impervious gloves.
- Feet** : Chemical resistant safety boots.

Protective clothing (pictograms)



- Personal protection in case of a large spill** : Splash goggles. Full suit. Boots. Gloves. Suggested protective clothing might not be sufficient; consult a specialist BEFORE handling this product.

Product name	Exposure limits
May contain: Nonane	ACGIH TLV (United States, 2003) TWA: 200 ppm 8 hour(s).
Decane	AIHA WEEL (United States) TWA: 45 ppm 8 hour(s).
Iso-paraffins	TWA: 250 mg/m ³ 8 hour(s).

9 Physical and chemical properties

- Physical state and appearance** : Clear liquid.
- Color** : Colourless.
- Odor** : Slight odour.
- Taste** : No data available.
- Molecular weight** : Not applicable.
- Molecular formula** : Not applicable.
- pH (1% soln/water)** : Not applicable.
- Boiling/condensation point** : 150-200°C
- Melting/freezing point** : No data available.
- Critical temperature** : No data available.
- Specific gravity** : 0.73 (Water = 1) @ 20°C
- Vapor pressure** : 7kPa @ 20°C
- Vapor density** : No data available.
- Volatility** : 100% w/w
- Odor threshold** : No data available.
- Evaporation rate** : No data available.
- VOC** : No data available.
- Viscosity** : Kinetic: 0.93 cSt @ 40°C

LogK_{ow} : No data available.
Ionicity (in water) : No data available.
Dispersion properties : No data available.
Solubility : Insoluble in water.
Physical chemical comments : No additional remark.

10 Stability and reactivity

Stability and reactivity : The product is stable.
Conditions of instability : Heat. Prolonged storage at elevated temperatures may interfere with quality.
Incompatibility with various substances : Avoid contact with strong oxidizing agents.
Hazardous decomposition products : Flue gas, carbon monoxide.
Hazardous polymerization : Will not occur.

11 Toxicological information

Toxicity to Animals : Acute toxicity of the vapor (LC50): 118 mg/m³ 4 hour(s) [Rat]. (n-Octane).
Chronic effects on humans : No data available.
Other toxic effects on humans : No known effects.
Special remarks on toxicity to animals : No additional remark.
Special remarks on chronic effects on humans : No additional remark.
Special remarks on other toxic effects on humans : No additional remark.

12 Ecological information

Ecotoxicity : No data available.
BOD and COD : No data available.
Biodegradable/OECD : Paraffins are biodegradable.
Mobility : No data available.
Products of degradation : No data available.
Toxicity of the products of biodegradation : No data available.
Special remarks on the products of biodegradation : No additional remark.

13 Disposal considerations

Waste information : Waste must be disposed of in accordance with federal, state and local environmental control regulations.
Waste stream : No data available.
Consult your local or regional authorities.

14 Transport information

Regulatory information	UN number	Proper shipping name	Class	Packing group	Label	Additional information
DOT Classification	UN 3295	HYDROCARBONS, LIQUID, N.O.S.	DOT Class 3: Flammable liquid.	III		-
TDG Classification	UN 3295	HYDROCARBONS, LIQUID, N.O.S.	TDG Class 3: Flammable liquid.	III		

Continued on Next Page

IMDG Class	UN 3295	HYDROCARBONS, LIQUID, N.O.S.	IMDG Class 3: Flammable liquid.	III		-
IATA-DGR Class	UN 3295	HYDROCARBONS, LIQUID, N.O.S.	IATA Class 3: Flammable liquid.	III		-

15 Regulatory information

HCS classification : Class: Combustible liquid having a flash point between 37.8°C (100°F) and 93.3°C (200°F).

U.S. Federal regulations : TSCA 4(a) proposed test rules: Nonane
TSCA 8(a) PAIR: Nonane
TSCA 8(b) inventory: n-Octane; Nonane; Decane; Undecane; Dodecane
TSCA 8(d) H and S data reporting: Nonane

SARA 302/304/311/312 extremely hazardous substances: No products were found.
SARA 302/304 emergency planning and notification: No products were found.
SARA 302/304/311/312 hazardous chemicals: No products were found.
SARA 311/312 MSDS distribution - chemical inventory - hazard identification: No products were found.

SARA 313 toxic chemical notification and release reporting: No products were found.

Clean Water Act (CWA) 307: No products were found.

Clean Water Act (CWA) 311: No products were found.

Clean air act (CAA) 112 accidental release prevention: No products were found.

Clean air act (CAA) 112 regulated flammable substances: No products were found.

Clean air act (CAA) 112 regulated toxic substances: No products were found.

State regulations : Connecticut hazardous material survey.: n-Octane
Rhode Island RTK hazardous substances: n-Octane; Nonane; Decane
Pennsylvania RTK: n-Octane; Nonane; Decane
Minnesota: n-Octane; Nonane
Massachusetts RTK: n-Octane; Nonane
Massachusetts spill list: n-Octane; Nonane
New Jersey: n-Octane; Undecane
New Jersey spill list: Decane

California prop. 65: No products were found.

EU Regulations

Hazard symbol(s) :



Classification : Harmful, Dangerous for the environment

Risk phrases : R10- Flammable.
R51/53- Toxic to aquatic organisms, may cause long-term adverse effects in the aquatic environment.
R65- Harmful: may cause lung damage if swallowed.
R66- Repeated exposure may cause skin dryness or cracking.
R67- Vapors may cause drowsiness and dizziness.

Safety phrases : S9- Keep container in a well-ventilated place.
S16- Keep away from sources of ignition - No smoking.
S24/25- Avoid contact with skin and eyes.
S60- This material and its container must be disposed of as hazardous waste.
S61- Avoid release to the environment. Refer to special instructions/Safety data sheets.
S62- If swallowed, do not induce vomiting: seek medical advice immediately and show this container or label.

EINECS Number : 203-913-4 (Nonane), 204-686-4 (Decane)

16 Other information

**National Fire
Protection
Association
(U.S.A.)**



References

- : - LOLI Database: The regulated Chemicals List of Lists.
- CHEMINFO: Canadian Centre for Occupational Health and Safety, Issue: 97-3 (August, 1997).- BDH; Hazard Data Disk, Version 3.- CESARS: Chemical Evaluation and Retrieval System, Produced by: Ontario Ministry of Environment and Michigan Department of Natural Resources, Issue:97-3 (August, 1997).- TOMES Plus System: Toxicology, Occupational Medicine & Environmental Series: incorporating:- MEDITEX, HAZARDTEXT, 1st Medical Response Protocols, INFOTEXT, HSDB, CHRIS, OHM/TADS, IRIS, NIOSH Pocket Guide, RTECS, NJ Fact Sheets, North American Emergency Response Guides, REPROTEXT, REPROTOX, TERIS, Shepard's Catalog of Teratogenic Agents.

Other special considerations

- : No additional remark.

Date of printing

: **11/21/2003.**

Date of issue

: **11/21/2003.**

Date of previous issue

: **No Previous Validation.**

Version

: **3**

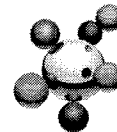
Verified by

: **Derick Johannes.**

Notice to reader

This MSDS summarises at the date of issue our best knowledge of the health, safety and environmental hazard information related to the product, and in particular how to safely handle, use, store and transport the product in the workplace. Since SASOL and its subsidiaries cannot anticipate or contr conditions under which the product may be handled, used, stored or transported, each user must, prior to usage, review this MSDS in the context of how the user intends to handle, use, store or transport the product in the workplace and beyond, and communicate such information to all relevant parties. If clarification or further information is needed to ensure that an appropriate assessment can be made, the user should contact this company.

We shall not assume any liability for the accuracy or completeness of the information contained herein or any advice given unless there has been gross negligence on our part. In such event our liability shall be limited only to direct damages suffered. Our responsibility for product as sold is subject to our standard terms and conditions, a copy of which is sent to our customers and is also available upon request. All risk associated with the possession and application of the product passes on delivery.



product data sheet

SSX™210

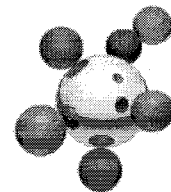
Code 1995 Revision 2 1 July 2003

Properties	Test method	Units	Specification	Typical values
Aromatics	ASTM D 1840	mass %	0.3 max	<0.1
Sulphur	Sasol 1.260	mg/kg	5 max	<1
Density @ 20°C	Sasol 1.173	kg/l	Report	0.7526
Colour	Sasol 1.31	Saybolt	+25 min	+30
Kinematic viscosity@ 40°C	ASTM D 445	cSt	Report	1.90
Flash point (closed cup)	ASTM D 93	°C	80 min	88
Distillation	ASTM D 86	°C		
Initial boiling point			205 min	215
Dry point			235 max	230
Bromine Index	ASTM D 2710	mg Br/100g	15 max	<10
Copper corrosion	ASTM D 130		Report	1a

Packaging

SSX™210 is available in bulk or in 210 litre drums.

Notice This product information is indicative and does not include any guarantee



Material Safety Data Sheet

SSX 210

1 Chemical product and company identification

Common name	: SSX 210	Code	: 1995
Supplier	: Sasol Wax P.O. Box 1 Sasolburg 1947 Republic of South Africa TEL: +27 16 960 3002	MSDS#	:
Synonym	: Normal hydrocarbon blend, Normal alkane, Normal aliphatic hydrocarbon blend .	Validation date	: 11/21/2003.
Trade name	: SSX 210	Print date	: 11/21/2003.
Material uses	: Mining industry: Diluent for mineral extraction in mining industry.	Prepared by	: Aneshia Ambaran.
Manufacturer	: Sasol Chemical Industries P.O. Box 1 Sasolburg 1947 Republic of South Africa TEL: +27 16 960-9111	In case of emergency	: SOUTH AFRICA: 0800 11 28 90 INTERNATIONAL: +27 17 610 4444

2 Composition / information on ingredients

Name	CAS #	% by weight	Exposure limits
Normal hydrocarbon blend Iso-paraffins	64771-72-8	90-100 0-10	

3 Hazards identification

Physical state and appearance	: Clear liquid.
Emergency overview	: WARNING! COMBUSTIBLE LIQUID AND VAPOR. HARMFUL IF SWALLOWED. Keep away from heat, sparks and flame. Keep container closed. Use only with adequate ventilation. If swallowed, seek medical advice immediately and show this container or label.
Routes of entry	: Absorbed through skin. Eye contact. Inhalation. Ingestion.
Potential acute health effects	
Eyes	: Hazardous in case of eye contact.
Skin	: Hazardous in case of skin contact.
Inhalation	: Hazardous in case of inhalation.
Ingestion	: Harmful if swallowed. Aspiration hazard if swallowed- can enter lungs and cause damage.
Potential chronic health effects	: CARCINOGENIC EFFECTS Not listed. MUTAGENIC EFFECTS Not listed. TERATOGENIC EFFECTS Not listed.
Medical conditions aggravated by overexposure:	: Repeated or prolonged exposure is not known to aggravate medical condition.

Overexposure /signs/symptoms : Inhalation of vapour can produce headache, drowsiness, dizziness, anaesthetic effect and central nervous system depression, which can lead to loss of coordination, numbness, impaired judgement, inability to concentrate and, if exposure is prolonged, unconsciousness.

See toxicological information (section 11)

4 First aid measures

Eye contact : Check for and remove any contact lenses. Immediately flush eyes with running water for at least 15 minutes, keeping eyelids open. Get medical attention.

Skin contact : In case of contact, immediately flush skin with plenty of water. Remove contaminated clothing and shoes. Wash clothing before reuse. Thoroughly clean shoes before reuse. Get medical attention.

Inhalation : If inhaled, remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. Get medical attention.

Ingestion : Do NOT induce vomiting unless directed to do so by medical personnel. Never give anything by mouth to an unconscious person. Loosen tight clothing such as a collar, tie, belt or waistband. If large quantities of this material are swallowed, call a physician immediately.

Notes to physician : Support respiratory and cardiovascular function.

5 Fire fighting measures

Flammability of the product : May be combustible at high temperature.

Autoignition temperature : No data available.

Flash points : Closed cup: 88°C (190.4°F).

Flammable limits : No data available.

Products of combustion : These are carbon oxides (CO, CO₂).

Fire hazards in presence of various substances : Flammable in presence of open flames, sparks, static discharge and oxidizing materials.

Explosion hazards in presence of various substances : Acids, alkalis and strong oxidisers.

Fire fighting media and instructions : SMALL FIRE: Use DRY chemical powder.
LARGE FIRE: Use water spray, fog or foam. Do not use water jet.

Protective clothing (fire) : Be sure to use an approved/certified respirator or equivalent.

Special remarks on fire hazards : No additional remark.

Special remarks on explosion hazards : No additional remark.

6 Accidental release measures

Small spill and leak : Absorb with an inert material and put the spilled material in an appropriate waste disposal.

Large spill and leak : Keep away from heat. Keep away from sources of ignition. Stop leak if without risk. Avoid inhalation of vapours. Contain – prevent run off into drains and waterways. Use absorbent (soil, sand or other inert material).

7 Handling and storage

Handling : Keep away from heat, sparks and flame. Keep container closed. Use only with adequate ventilation. To avoid fire, minimize ignition sources. Do not ingest.

Storage : Keep container in a cool, well-ventilated area. Keep container tightly closed and sealed until ready for use. Avoid all possible sources of ignition (spark or flame).

8 Exposure controls, personal protection

Engineering controls : Provide exhaust ventilation or other engineering controls to keep the airborne concentrations of vapors below their respective occupational exposure limits. Ensure that eyewash stations and safety showers are proximal to the work-station location.

Personal protection

Eyes : Splash goggles.

Body : Chemical resistant protective suit.

Respiratory : Vapor respirator. Be sure to use an approved/certified respirator or equivalent. Wear appropriate respirator when ventilation is inadequate.

Hands : Impervious gloves.

Feet : Chemical resistant safety boots.

Protective clothing (pictograms) :



Personal protection in case of a large spill : Splash goggles. Full suit. Boots. Gloves. Suggested protective clothing might not be sufficient; consult a specialist BEFORE handling this product.

Product name

Normal hydrocarbon blend
Iso-paraffins

Exposure limits

9 Physical and chemical properties

Physical state and appearance : Clear liquid.

Color : Colourless.

Odor : Odourless.

Taste : No data available.

Molecular weight : Not applicable.

Molecular formula : Not applicable.

pH (1% soln/water) : Not applicable.

Boiling/condensation point : 200-240°C

Melting/freezing point : No data available.

Critical temperature : No data available.

Specific gravity : 0.75 (Water = 1) @ 20°C

Vapor pressure : <7 kPa @ 37.8°C

Vapor density : No data available.

Volatility : No data available.

Odor threshold : No data available.

Evaporation rate : No data available.

VOC : No data available.

Viscosity : Kinetic: 1.59 cSt @ 40°C

LogK_{ow} : No data available.

Ionicity (in water) : No data available.

Dispersion properties : No data available.

Solubility : Insoluble in water.

Physical chemical comments : No additional remark.

10 Stability and reactivity

Stability and reactivity : The product is stable.

Conditions of instability : Heat. Prolonged storage at elevated temperatures may interfere with quality.

Incompatibility with various substances : Avoid contact with strong oxidizing agents.

Hazardous decomposition products : Flue gas, carbon monoxide.

Hazardous polymerization : Will not occur.

11 Toxicological information

- Toxicity to Animals** : No data available.
- Chronic effects on humans** : No data available.
- Other toxic effects on humans** : No specific information is available in our database regarding the other toxic effects of this material for humans.
- Special remarks on toxicity to animals** : No additional remark.
- Special remarks on chronic effects on humans** : No additional remark.
- Special remarks on other toxic effects on humans** : No additional remark.

12 Ecological information

- Ecotoxicity** : No data available.
- BOD and COD** : No data available.
- Biodegradable/OECD** : Paraffins are readily biodegradable.
- Mobility** : No data available.
- Products of degradation** : No data available.
- Toxicity of the products of biodegradation** : No data available.
- Special remarks on the products of biodegradation** : No additional remark.

13 Disposal considerations

- Waste information** : Waste must be disposed of in accordance with federal, state and local environmental control regulations.
- Waste stream** : No data available.
- Consult your local or regional authorities.**

14 Transport information

Regulatory information	UN number	Proper shipping name	Class	Packing group	Label	Additional information
DOT Classification	Not applicable.	Not regulated.	Not a DOT controlled material (United States).	Not applicable		-
TDG Classification	Not applicable	Not regulated.	Not controlled under TDG (Canada).	Not applicable		-
IMDG Class	Not applicable	Not regulated.	Not controlled under IMDG.	Not applicable		-
IATA-DGR Class	Not applicable	Not regulated.	Not controlled under IATA.	Not applicable		-

15 Regulatory information

- HCS classification** : Class: Combustible liquid having a flash point between 37.8°C (100°F) and 93.3°C (200°F).
- U.S. Federal regulations** : TSCA 8(b) inventory: Undecane; Dodecane; Tridecane;
SARA 302/304/311/312 extremely hazardous substances: No products were found.
SARA 302/304 emergency planning and notification: No products were found.
SARA 302/304/311/312 hazardous chemicals: No products were found.
SARA 311/312 MSDS distribution - chemical inventory - hazard identification: No products were found.
SARA 313 toxic chemical notification and release reporting: No products were found.

Clean Water Act (CWA) 307: No products were found.

Clean Water Act (CWA) 311: No products were found.

Clean air act (CAA) 112 accidental release prevention: No products were found.

Clean air act (CAA) 112 regulated flammable substances: No products were found.

Clean air act (CAA) 112 regulated toxic substances: No products were found.

State regulations

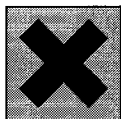
: New Jersey: Undecane

California prop. 65: No products were found.

EU Regulations

Hazard symbol(s)

:



Classification

: Harmful

Risk phrases

: R65- Harmful: may cause lung damage if swallowed.
R66- Repeated exposure may cause skin dryness or cracking.
R67- Vapors may cause drowsiness and dizziness.

Safety phrases

: S24/25- Avoid contact with skin and eyes.
S62- If swallowed, do not induce vomiting: seek medical advice immediately and show this container or label.

EINECS Number

: 211-093-4 (Tridecane), 203-967-9 (Dodecane), 214-300-6 (Undecane), 211-090-6 (Tetradecane)

16 Other information

National Fire Protection Association (U.S.A.)



References

: - LOLI Database: The regulated Chemicals List of Lists.
- CHEMINFO: Canadian Centre for Occupational Health and Safety, Issue: 97-3 (August, 1997).- BDH; Hazard Data Disk, Version 3.- CESARS: Chemical Evaluation and Retrieval System, Produced by: Ontario Ministry of Environment and Michigan Department of Natural Resources, Issue:97-3 (August, 1997).- TOMES Plus System: Toxicology, Occupational Medicine & Environmental Series: incorporating:- MEDITEX, HAZARDTEXT, 1st Medical Response Protocols, INFOTEXT, HSDB, CHRIS, OHM/TADS, IRIS, NIOSH Pocket Guide, RTECS, NJ Fact Sheets, North American Emergency Response Guides, REPROTEXT, REPROTOX, TERIS, Shepard's Catalog of Teratogenic Agents.

Other special considerations

: No additional remark.

Date of printing

: 11/21/2003.

Date of issue

: 11/21/2003.

Date of previous issue

: No Previous Validation.

Version

: 3

Verified by

: Derick Johannes.

Notice to reader

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We shall not assume any liability for the accuracy or completeness of the information contained herein or any advice given unless there has been gross negligence on our part. In such event our liability shall be limited only to direct damages suffered. Our responsibility for product as sold is subject to our standard terms and conditions, a copy of which is sent to our customers and is also available upon request. All risk associated with the possession and application of the product passes on delivery.



Data Sheet

Issued:

23-Jul-2009

Product Name**ShellSol D70****Product Code****Q7712 Africa****Product Category****Aliphatics****CAS Registry Number**

64742-47-8

EINECS Number

265-149-8

Description

ShellSol D70 is a very low aromatic, inert hydrocarbon solvent.

Typical Properties

Property	Unit	Method	Value
Density @15°C	kg/l	ASTM D4052	0.793
Density @20°C	kg/l	ASTM D4052	0.790
Cubic Expansion Coefficient @20°C	(10 ⁻⁴)/°C	-	9
Refractive Index @20°C	-	ASTM D1218	1.436
Color	Saybolt	ASTM D156	+30
Distillation, IBP	°C	ASTM D1078	200
Distillation, DP	°C	ASTM D1078	240
Relative Evaporation Rate (nBuAc=1)	-	ASTM D3539	0.01
Vapor Pressure @20°C	kPa	Calculated	0.05
Saturated Vapor Concentration @20°C	g/m ³	Calculated	4
Paraffins	% m/m	GC	60
Naphthenes	% m/m	GC	40
Aromatics	% m/m	SMS 2728	< 0.5
Benzene	mg/kg	GC	< 3
Sulfur	mg/kg	ASTM D5453	< 10
Flash Point	°C	ASTM D93	77
Explosion Limit: Lower	%v/v	-	0.6
Explosion Limit: Upper	%v/v	-	5.5
Electrical Conductivity @20°C	pS/m	-	< 1
Aniline Point	°C	ASTM D611	77
Pour Point	°C	ASTM D97	< -50
Surface Tension @20°C	mN/m	Du Nouy ring	26
Viscosity @25°C	mm ² /s	ASTM D445	2.0
Hildebrand Solubility Parameter	(cal/cm ³) ^{1/2}	-	7.6
Hydrogen Bonding Index	-	-	0

	Fractional Polarity - - 0 Molecular Weight g/mol Calculated 174
Test Methods	Copies of copyrighted test methods can be obtained from the issuing organisations: American Society for Testing and Materials (ASTM) : www.astm.org Shell Method Series (SMS) methods are issued by Shell Global Solutions International B.V., Shell Research and Technology Centre, Amsterdam, The Netherlands. Copies of SMS can be obtained through your local Shell Chemicals company. For routine quality control analyses, local test methods may be applied that are different from those mentioned in this datasheet. Such methods have been validated and can be obtained through your local Shell Chemicals company.
Quality	ShellSol D70 does not contain detectable quantities of polycyclic aromatics, heavy metals or chlorinated compounds.
Storage and Handling	Provided proper storage and handling precautions are taken we would expect ShellSol D70 to be technically stable for at least 12 months. For detailed advice on Storage and Handling please refer to the Material Safety Data Sheet on www.shell.com/chemicals
Hazard Information	For detailed Hazard Information please refer to the Material Safety Data Sheet on www.shell.com/chemicals.
Warranty	All products purchased or supplied by Shell Chemicals are subject to terms and conditions set out in the contract, order acknowledgment and/or bill of lading. Shell Chemicals warrant that their product will meet those specifications designated as such herein or in other publications. All other information including that herein, supplied by Shell Chemicals is considered accurate but is furnished upon the express condition that the customer shall make its own assessment to determine the products' suitability for a particular purpose. Shell Chemicals make no other warranty either expressed or implied, regarding such other information, the data upon which the same is based, or the results to be obtained from use thereof; that any products shall be merchantable or fit for any purpose; or that the use of such other information or product will not infringe any patent. The expression 'Shell Chemicals' refers to the companies of the Shell Group that are engaged in chemical businesses. Each of the companies that make up the Shell Group of companies is an independent entity and has its own separate identity.
Trademark	ShellSol is a Shell Trademark.



Data Sheet

Issued:

23-Jul-2009

Product Name**ShellSol 2325****Product Code****Q3351 Africa****Product Category****White Spirits****CAS Registry Number**

64742-81-0

EINECS Number

265-184-9

Description

ShellSol 2325 is a wide cut mixture of paraffins, cycloparaffins and aromatics that boils in between 220 and 250°C. As a consequence of its increased boiling range level ShellSol 2325 can be considered as a high flash, slow evaporating type of hydrocarbon solvent.

Typical Properties

Property	Unit	Method	Value
Density @20°C	kg/l	ASTM D4052	0.814
Cubic Expansion Coefficient @20°C	(10 ⁻⁴)/°C	-	9
Refractive Index @20°C	-	ASTM D1218	1.452
Color	Saybolt	ASTM D156	+30
Distillation, IBP	°C	ASTM D1078	217
Distillation, 50%v	°C	ASTM D1078	226
Distillation, DP	°C	ASTM D1078	241
Relative Evaporation Rate (nBuAc=1)	-	ASTM D3539	0.01
Paraffins	% m/m	GC	44
Naphthenes	% m/m	GC	35
Aromatics	%v/v	ASTM D1319	19
Benzene	mg/kg	GC	< 10
Sulfur	mg/kg	ASTM D5453	< 20
Flash Point	°C	ASTM D93	89
Explosion Limit: Lower	%v/v	-	0.7
Explosion Limit: Upper	%v/v	-	6.5
Electrical Conductivity @20°C	pS/m	-	< 1
Aniline Point	°C	ASTM D611	64
Pour Point	°C	ASTM D97	< -30
Surface Tension @20°C	mN/m	Du Nouy ring	28
Viscosity @25°C	mm ² /s	ASTM D445	2.2
Hildebrand Solubility Parameter	(cal/cm ³) ^{1/2}	-	7.7
Hydrogen Bonding Index	-	-	0.4

	Fractional Polarity	-	-	0
	Molecular Weight	g/mol	Calculated	174
Test Methods	Copies of copyrighted test methods can be obtained from the issuing organisations: American Society for Testing and Materials (ASTM) : www.astm.org For routine quality control analyses, local test methods may be applied that are different from those mentioned in this datasheet. Such methods have been validated and can be obtained through your local Shell Chemicals company.			
Applications	ShellSol 2325 primary usage is as a solvent in metallurgical applications such as the liquid/liquid extraction of Copper , Uranium and other precious metals . It is also used as a fuel in the manufacture of explosives for the mining industry and in printing inks . ShellSol 2325 exceeds the Chamber of Mines flash point requirements for solvents, used underground.			
Hazard Information	For detailed Hazard Information please refer to the Material Safety Data Sheet on www.shell.com/chemicals ("Health, Safety & Environment").			
Storage and Handling	Provided proper storage and handling precautions are taken we would expect ShellSol 2325 to be technically stable for at least 12 months. For detailed advice on Storage and Handling please refer to the Material Safety Data Sheet on www.shell.com/chemicals ("Health, Safety & Environment").			
Warranty	All products purchased or supplied by Shell Chemicals are subject to terms and conditions set out in the contract, order acknowledgment and/or bill of lading. Shell Chemicals warrant that their product will meet those specifications designated as such herein or in other publications. All other information including that herein, supplied by Shell Chemicals is considered accurate but is furnished upon the express condition that the customer shall make its own assessment to determine the products' suitability for a particular purpose. Shell Chemicals make no other warranty either expressed or implied, regarding such other information, the data upon which the same is based, or the results to be obtained from use thereof; that any products shall be merchantable or fit for any purpose; or that the use of such other information or product will not infringe any patent. The expression 'Shell Chemicals' refers to the companies of the Shell Group that are engaged in chemical businesses. Each of the companies that make up the Shell Group of companies is an independent entity and has its own separate identity.			
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