MICROWAVE EFFECTIVENESS IN HEAVY OIL EXTRACTION:

THE ROLE OF CRUDE OIL COMPOSITION

A Thesis

by

HUAIQI LIAO

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Berna Hascakir
Committee Members,	YueFeng Sun
	Samuel Noynaert
Head of Department,	Jeffrey Spath

May 2019

Major Subject: Petroleum Engineering

Copyright 2019 Huaiqi Liao

ABSTRACT

Microwave heating as a thermal enhanced oil recovery (EOR) method has the potential to significantly reduce the total heating time of a reservoir and, consequently, the total cost of oil production. Success of microwave heating is controlled by the dielectric properties of the materials subjected to microwave radiation. Hence, this study investigates the dielectric properties of crude oil fractions, namely saturates, aromatics, resins, and asphaltenes (SARA) on microwave effectiveness of heavy oil extraction.

In this study, three oil samples with distinct differences in API, viscosity, and SARA weight percentages were tested for their microwave heating effectiveness. Asphaltenes are defined as the most polar fraction within crude oil, so further investigation of its effect to crude oil absorption is merited. Upon oil fractionation through the ASTM method in conjunction with microwave heating, three major components of crude oil composition were investigated to maximize absorption in the oil phase: alteration of asphaltene polarity through various solvents, polar-polar interactions between resins and asphaltenes, and the temperature dependence of dielectric properties with respect to crude oil composition. Solvents selected comprised of two asphaltene precipitants (nC5 & nC7) and an asphaltene dispersant (toluene) were added to bulk crudes at discrete weight percentages (10%, 20%, and 50%). Dielectric property dependence on temperature was compared between the microwaved results and samples heated conventionally at various temperatures.

A temperature dependence was connected to the bulk crude oils, where both the dielectric constant and loss tangent are more prone to increase when exposed to increased

temperatures. Temperature correlations depicted that as the API increased for various oils, viscosity would necessarily decrease. Crude oils with the highest weight percentages of resins and asphaltenes (20.14%, 40.08%), lowest API (6.11), and highest viscosity (1.00E+07) led to the greatest increase in the dielectric constant, or polarity of the crude oil (2.26%). Conversely, oil samples with the highest light components in saturates and aromatics (30.03%, 41.84%), highest API (17.12%), and lowest viscosity (496) will produce the highest absorption difference in the loss tangent (121.54%). As it was found that the dielectric properties are highly sensitive to temperature, colloidal instability index should not be used as the main indicator of dielectric performance prediction. Microwaved results mostly echo that of the conventional results, but the difference in performance varied. Further research would necessitate altering various microwaving parameters such as the heating time and frequency to achieve desired results.

The aforementioned correlations offers a fast and easy method to identify the potential of given crude oils for microwave heating. For the first time, heavy oil and its SARA fractionations were investigated on a deeper scale on how microwave absorption can be maximized.

ACKNOWLEDGEMENTS

First, I would like to thank Drs. Noynaert and Sun for agreeing to be on my committee and supporting my master's research. I would also like to thank Dr. Hascakir for giving me all the support I needed to finish this thesis, despite the various obstacles. Without her guidance, this would never have been possible.

Next, I would like to thank my fellow members of the HOCAM research group, all of whom helped me in a variety of ways. Finally, I would like to thank my family and friends for encouraging me to pursue this master's degree.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a committee consisting of Professor and Chair Berna Hascakir, Professor Sam Noyaert of the Department of Petroleum Engineering and Professor Yuefeng Sun of the Department of Geology and Geophysics.

Some experimental data has been collected from collaboration with Dr. Gregory Huff of Department of Electrical Engineering.

All other work conducted for the thesis was completed by the student, independently.

Funding Sources

The Graduate Study was supported through the Gates Millennium Scholarship, from the Bill and Melinda Gates foundation.

NOMENCLATURE

API	American Petroleum Institute
ASTM	American Society for Testing and Materials
C	Coulomb
D	Debye
DAO	Deasphalted Oil
FTIR	Fourier Transformed InfraRed Spectroscopy
nC5	n-pentane
nC7	n-heptane
D_p	Penetration Depth
SARA	Saturates, Aromatics, Resins, Asphaltenes
ε’	Dielectric Constant
ε’’	Loss Index
tanδ	Loss Tangent

TABLE OF CONTENTS

Page

ABSTRACT ii

ACKNOWLEDGEMENTS……………………………………………………………...iv

CONTRIBUTORS AND FUNDING SOURCES……………...………………………...v

NOMENCLATURE……………………………………………………………………..vi

TABLE OF CONTENTS vii

LIST OF FIGURES viii

LIST OF TABLES x

1. INTRODUCTION 1

2. EXPERIMENTAL PROCEDURE 10

3. RESULTS AND DISCUSSION 15

4. CONCLUSIONS……………………………………………………………… 44

REFERENCES 47

APPENDIX……………………………………………………………………...52

LIST OF FIGURES

Page

Figure 1: Weight percentages of nC5 and nC7 insoluble asphaltenes for all three crude oil samples 16

Figure 2: Weight percentages of nC5 and nC7 insoluble asphaltenes for all crude samples before and after microwave exposure for 3 minutes 21

Figure 3: Dielectric constants of C1 crude oil blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentrations before and after 3 minute microwave exposure ....…..23

Figure 4: Dielectric loss indexes of C1 crude oil blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentration before and after 3 minute microwave exposure……...…..25

Figure 5: Dielectric loss tangents of C1 crude oil blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentrations before and after 3 minute microwave exposure ....…..26

Figure 6: Penetration depths of C1 crude oil blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentrations before and after 3 minute microwave exposure ....…..28

Figure 7: Dielectric constants of crude oil C2 blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentrations before and after 3 minute microwave exposure...29

Figure 8: Dielectric loss indexes of crude oil C2 blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentrations before and after 3 minute microwave exposure ....…..30

Figure 9: Dielectric loss tangents of crude oil C2 blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentrations before and after 3 minute microwave exposure…...……………………………………………………………..…31

Figure 10: Penetration depths of crude oil C2 blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentrations before and after 3 minute microwave exposure……..……………………………………………………………… ……….32

Figure 11: Dielectric constants of C3 crude oil blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentrations before and after 3 minute microwave exposure ………………...33

Figure 12: Dielectric loss indexes of C3 crude oil blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentrations before and after 3 minute microwave exposure …………………..…………..……………………………………34

Figure 13: Dielectric loss tangents of C3 crude oil blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentrations before and after 3 minute microwave exposure ………..…………………………………………………………..35

Figure 14: Penetration depths of C3 crude oil blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentrations before and after 3 minute microwave exposure…………………………….……………………………………36

Figure 15: Correlations on the contribution of toluene for all crude oil samples before microwave at 2.45 GHz…………………………………………………….………37

Figure 16 – Dielectric Constant and Loss Tangent of crude oils C1, C2 and C3 at varying temperatures…………………………...……………………………………..41

LIST OF TABLES

Page

Table 1.1 – Dielectric Constants of Common Reservoir Rocks, Fluids, Minerals Measured at 100 MHz... 7

Table 2.1 – Characterization of the Crude Oil Samples Used in this Study...…………..11

Table 3.1 – Dielectric Properties of Bulk Crude and Fractionations for Three Crude Oils Before and After Microwave Heating at 2.45 GHz………………………………..16

Table 3.2 – Dielectric Properties of Resins and Asphaltenes Mixtures for All Three Crude Oils before and After Microwave Heating at 2.45 GHz…………….…………...39

Table 3.3 – Crude oil Properties with Correlation to Temperature Dependence Results for Dielectric Properties ..…………………………..………………………………..41

Table 3.4 – Crude oil Properties with Correlation to Microwave Heating Results for Dielectric Properties ………………………………..………………………………..43

1. INTRODUCTION

The global demand for petroleum has increased steadily over the last few years, with projections for future demands indicating a further rise (Kontorovich, 2009). Conventional reserves are decreasing as global production is expanding to meet demands, especially with regard to heavy oil and bitumen production. These two products account for about 70% of the world's reserves (Keijing et al., 2013). Specifically, there are currently 3,396 billion barrels of heavy oil in place and 5,505 billion barrels of bitumen known to be in place (USGS, 2007). Crude oil is termed as either heavy oil or bitumen, based on the density at standard conditions and viscosity at reservoir conditions. Oil with a viscosity above 10,000 cP at reservoir conditions, regardless of density, is called bitumen; below 10,000 cP, categorization is made based on API gravity. Light oil has an API of 25^{o} or greater, medium oil is between 25^{o} and 20^{o} API, heavy oil is between 20^{o} and 10^{o} API, and extra-heavy oil is less than 10^{o} API (Meyer, 2003). Heavy oil and bitumen are very difficult to produce due to their high viscosity values (Prats, 1982; Beal, 1946). Other difficulties with heavy oil and bitumen extraction include high densities, substantial capital investment, and negative environmental impacts (Keijing et al., 2013).

Because of the temperature sensitivity of viscosity, introducing heat into a reservoir increases the mobility of heavy oils (Reynolds, 1996; Bird et al., 1960). Hence, thermally enhanced oil recovery (EOR) methods are frequently implemented to extract heavy oil and bitumen (Burger et al., 1985). Steam injection is the prevalent thermal EOR method due to its reliability, accounting for more than 50% of the overall EOR market. However, this method has its disadvantages. Ideally, steam injections are done at shallow depths because steam generation cannot be achieved deeper than 4,500 feet. At that point, the steam injection process turns into hot water flooding (Meyer et al., 2007). Steam generation also requires a large supply of high-quality fresh water and results in emissions of greenhouse gases such as CO_2, making the process environmentally unfriendly (Acosta, 2010; Kovscek, 2012). Other issues include substantial heat loss through the overburden when the process is applied to thin reservoirs (Hascakir et al., 2008), due to inhomogeneous heat distributions in the heterogeneity of the reservoirs, which is caused by permeability zones and fractures (Chakma & Jha, 1992; Sahni & Kumar, 2000; Huang et al., 2015).

Thus, electromagnetic heating is proposed as a means of overcoming challenges faced by steam injection and other thermal EOR methods (Abernethy, 1976; Chhetri & Islam, 2008). Electromagnetic heating can achieve much faster heating times at reduced costs, as compared to conventional heating; this is due to the volumetric homogenous distribution of heat (Osepchuk, 1984). There are fewer heat losses caused by the overburden and underburden due to preferential heating, and advantages are seen in heterogeneous reservoirs from the intrinsic wave propagation of all materials (Mutlaya et al., 2010). Furthermore, this is more energy-efficient, since the heating can be isolated to specific zones (Jones et al., 2002). This type of heating can also be applied to thin pay-zones where heat losses are significant in adjacent formations (Sahni et al., 2000).

There are also several drawbacks to microwave heating that must be addressed. When applied on a field scale, it is an extremely energy-intensive method that can also be inefficient, depending on the depth at which it is applied (Sahni et al., 2000). Poor penetration depths result beyond a certain depth, due to the high attenuation of the wave (Mullin, 1995; Chetri & Islam, 2008). Moreover, it is often very difficult to model microwave heating's absorption and penetration behaviors, because of the complexity of the materials in reservoirs with independent dielectric properties (Ohlsson & Risman, 1978).

The electromagnetic wave spectrum ranges from high-frequency waves such as gamma rays (10^{19} Hz and above) to low-frequency waves such as radio and microwaves (300 MHz to 300 GHz) (Roberts & Cook, 1952). The heating output is highly dependent upon the input frequency selected. Within the radio and microwave frequency ranges, at lower frequencies ionic conduction dominates, while at higher frequencies dielectric heating is most prevalent (Wang, 1986). Ionic conduction occurs when ions are transferred between positively and negatively charged ions in the presence of an aqueous solution, usually water. Vibrational movement generated from the phenomenon generates heat (Gude et al., 2013). Dielectric heating occurs when small electromagnetic fields are generated from oscillating high-frequency waves of opposite charges, from which molecules attempt to align themselves with the fields, causing electric polarization (Onsager, 1936; Harris & Alder, 1953; Harris & Konski, 1957). Dipole rotations associated with this alignment are directly related to the polarity of the molecules, from which the vibrational movement and rotation of molecules generate heat (von Hippel, 1954).

Polarity is primarily responsible for the dipole rotations generated from microwaves. Polarity represents the electrical charges between atoms joined by a chemical bond. The polarity values are found from relative electronegativities, or the relative ability of an atom to attract electrons in a chemical compound of the individual elements of the bond (Silvi & Savin, 1994). As a rule, overall bond polarity increases as the difference in total electronegativity grows (Harris & Alder, 1953). Three common types of bonds usually found within chemical compounds include nonpolar covalent bonds such as Cl_2, which have their electrons shared equally with no net charge; polar covalent bonds such as HCl, which contain an unequal sharing of electrons that causes partial positive and negative charges of the respective ions; and ionic bonds such as NaCl, which perform a complete transfer of electrons for a full charge on the ions (Pauling, 1932). Asymmetry in the bonding can also yield a difference in electronegativity, depending on the bending angle (Brown et al., 2008). For example, CO_2 does not have a bonding angle and has no polarity, while H_2O has bending angles that produce highly polar molecules (Brown et al., 2008).

Dipole moments caused by the asymmetrical distribution of electrical charges can be defined by the following mathematical equation (Harris & Alder, 1953):

$$\mu\,(D) = Qr \tag{1}$$

where Q represents partial charges due to the asymmetrical distribution of electrons, r is the distance between the charges, and the units of Debye (D) are defined as $3.3356*10^{-30}$ C*m. From the previous discussion, it is clear that non-polar symmetrical molecules will create 0 dipole moments, while polar molecules with differences in electro-negativities or asymmetries in their molecular structure will generate positive dipole moments. Polarity can be defined as the summation of dipole moments across a differential volume (Equation 2), which are directly related to dielectric properties:

$$P = \frac{\sum_{i=1}^{N} q_i r_i}{\delta v} \tag{2}$$

where q represents partial charges due to an asymmetrical distribution of electrons, and r is the distance between the charges. Thus, $q_i r_i$ indicates the dipole moment of component i and δv represents the differential volume of the applied dipole moments.

Dielectric properties are closely related to the efficiency of microwave heating, consisting of the dielectric constant, dielectric loss index, and loss tangent (Hennelly et al., 1948). The dielectric constant, ε', characterizes a material's ability to polarize under an electromagnetic field (Wyman, 1936). For heating purposes, the dielectric constant also characterizes a material's ability to store electromagnetic charge (von Hippel, 1954). The dielectric loss factor, ε'', measures a material's loss of energy through polarization and other phenomena (Hamon et al., 1952; Krupka et al., 1988). The loss factor accounts for the amount of energy lost in the material dissipated as heat, due to unideal heat transfer. Finally, the loss tangent indicates a material's microwave energy absorption (Weir, 1974). The absorbance can be classified as transparent (i.e., sulfur), reflective or opaque (i.e., metals), or absorbent (i.e., water), from which absorbers can generate selective heating for higher levels of efficiency (Mullin, 1995; Mutyala et al., 2010).

Although penetration depth is not a dielectric property, it is a large limiting factor in the effectiveness of microwave heating, and therefore should be calculated. Penetration depth is often a variable of interest for energy balance, due to the fast attenuation of electromagnetic waves that leads to lower penetration depths (Mullin, 1995; Meredith et al., 1983). Thus, to determine overall microwave efficiency, it is important to investigate parameters outside of dielectric properties. The microwave penetration depth is defined as the distance of a dielectric material at which incident power drops to 1/e or 37% (Ohlsson, 1974), and is calculated by the following equation:

$$D_p = \frac{\lambda_0}{2\pi\sqrt{2\varepsilon'}}\left(\sqrt{1+(tan\delta)^2}-1\right)^{-0.5} \quad (3)$$

where λ_0 is the microwave wavelength in free space (m), $\varepsilon'$is the dielectric constant, and $tan\delta$ is the loss tangent. The loss tangent is defined and calculated by the following formula:

$$tan\delta = \frac{\varepsilon''}{\varepsilon'} \quad (4)$$

where ε'' represents the dielectric loss index and ε' indicates the dielectric constant.

Simultaneously maximizing both penetration depth and absorption is not possible, due to their inverse relationship to one another (Thostenson & Chou, 1999). Higher penetration depths can be achieved, but with the consequence that less heat is delivered to the material (Metaxas & Meredith, 1983). Lower penetration depths are achieved relative to low-frequency heating, although waves of higher frequencies are less susceptible to permeability, porosity, and heterogeneity, and generate more heat (Metaxas and Meredith, 1983). Due to the industrial preference for the higher absorption rates that yield efficient microwave projects, the focus of this research is on high-frequency microwave heating.

When applied in an oil field, the effectiveness of microwave heating is highly dependent upon the dielectric properties of the material. Table 1.1 summarizes the dielectric constants of common reservoir rocks, fluids, and minerals.

Table 1.1 - Dielectric Constants of Common Reservoir Rocks, Fluids, and Minerals Measured at 100 MHz (Shen et al., 1985; Lucius et al., 1989)

Common Reservoir Rocks		**Common Reservoir Fluids/Minerals**	
Material	**Dielectric Constant**	**Material**	**Dielectric Constant**
Air	1	Acetone	20.9
Distilled water	80	Albite	7
Fresh water	80	Benzene	2.3
Permafrost	4 to 8	Calcite	6.4
Snow	8 to 12	Carbon tetrachloride	2.2
Sand (dry)	4 to 6	Gypsum	6.5
Sand (wet)	10 to 30	Halite	5.9
Sandstone (dry)	2 to 3	Ice	3.4
Sandstone (wet)	5 to 10	Kaolinite	11.8
Limestone	4 to 8	Methanol	33.6
Shales	5 to 15	Mica	6.4
Silts	5 to 30	Olivine	7.2
Clays	5 to 40	Orthoclase	5.6
Granite	4 to 6	Pyroxene	8.5
Salt	4 to 7	Quartz	4.5

Of the most common materials, water has the most substantial effect on dielectric properties, as compared to any other constituent, due to its high dielectric constant of 80 and high polarity (Shen et al., 1985). Thus, because of its higher dielectric constant, saturated rock has a higher capacity to store electromagnetic energy (Martinez and Byrnes, 2001). Because of changes in the type and volume of fluid occupying the pore space, reservoir rock properties such as porosity can directly impact microwave heating in a reservoir (Martinez & Byrnes, 2001).

Although there have been relatively few studies of field and simulated applications of microwave heating, those that exist show great potential (Sresty et al., 1986; Spencer, 1987; Kasevich et al., 1994; Mukhametshina & Martynova, 2013). Thin pay zone reservoirs achieved the highest rate of original oil in place, at 45% (Chakma & Jha, 1992). Turkish oil tested with high water saturation in water-wet conditions resulted in higher overall recoveries (Hascakir et al., 2008). Field tests were performed in Denver to compare low and high-power tests at a depth of 620 feet; the results showed a high antenna downhole efficiency of 99.9%, demonstrating that the electromagnetic heating method is capable of favorable returns (Kasevich et al., 1994). The Wildmere field in Alberta, Canada, also enabled electromagnetic heating; the production increased from .95 tonnes/day to 3.18 tonnes/day over a period of six months (Spencer, 1987).

Aside from field and simulation studies, little work has been done toward understanding the role of crude oil composition in microwave effectiveness. However, crude oil fractionations (i.e., saturates, aromatics, resins, and asphaltenes) can directly impact the outcome of microwave heating (Kar & Hascakir, 2015; Morte et al., 2018; Alshaikh et al., 2018). Asphaltenes comprise the most polar fraction of crude oil (Speight 1991; Mullins, 1998); they are macromolecules containing aromatic and naphthenic cores, aliphatic chains, and heteroatoms such as oxygen, nitrogen, and sulfur (Padovani et al., 1959). Hence, they exist in complex molecular structures, without having a unique molecular formula (Speight, 1994). They are also soluble in aromatic solvents (e.g., toluene), and insoluble in paraffinic solvents (i.e., n-heptane) (Padovani et al., 1959).

Resins are another polar fraction of crude oil (Jewell et al., 1972). Since resins and asphaltenes are the most polar components of crude oil, their impact on microwave heating is higher than the non-polar fractions in saturates and aromatics (Punase et al., 2016; Mullins et al., 2007). While asphaltenes control microwave absorption due to having the highest polarity among all four fractionations, there has been only limited research on their fundamental interactions (Speight, 1994). Most research on asphaltenes has followed the classical colloidal model, suggesting that solid particles form a core of stacks of asphaltenes surrounded by aromatics and resins molecules. Traditional theory regarding asphaltenes stability states that the less-polar resins molecules orient their polar heads toward the asphaltenes' surfaces to form a steric protective layer. Therefore, asphaltenes dispersed in crude oil are surrounded by a shell of resins. Thus, the mutual interactions between resins and asphaltenes control microwave absorption (Kar & Hascakir, 2015).

This research examined the role of crude oil composition in relation to its fractions, and determined how it directly impacts microwave absorption.

2. EXPERIMENTAL PROCEDURE

This study investigated the microwave absorption characteristics of three oil samples. The API gravity and viscosity of the crude oils were determined by following the ASTM D287 and ASTM D445 methods, respectively. Density measurements were taken by an Anton Paar 4500 M densitometer. Saturates, aromatics, resins, and asphaltenes (SARA) fractionation was conducted based on ASTM-D2007-11, first by employing n-pentane to separate the asphaltenes (ASTM-D2007-11). SARA fractionation began with separating the asphaltenes from the crude oil via n-pentane, as the precipitant solvent. The remaining solution, the deasphalted oil, then underwent two separate columns. The top was filled with attapulgus clay, which served to separate the resins through a 1:1 mixture of toluene and acetone. The bottom contained a layer of silica gel covered by attapulgus clay, in order to separate saturates and aromatics. The aromatics fraction was partially adsorbed by the clay, while the rest was adsorbed to the silica gel. Finally, saturates were not adsorbed by either layer and instead were collected in an Erlenmeyer flask.

A more polar solvent, n-heptane, was also used to separate asphaltenes via another ASTM procedure (ASTM D3279-12); this allowed for observation of the asphaltenes' behavior of varying their polarity in crude oil mixtures (Shkalikov et al., 2010). The weight of the n-pentane and n-heptane insoluble asphaltenes was determined (Prakoso et al., 2017). Table 2.1 shows the characteristics of the three crude oil samples (i.e., C1, C2, and C3) after they were subjected to the microwave heating experiments. In Table 2.1, the viscosity, density, saturates, aromatics, resins, and asphaltenes values for all three crude oil samples are reported. The viscosity, asphaltenes weight percent, and resins weight percent were all considered before selecting the oil samples. We defined asphaltene stability according to the colloidal instability index (CII), which is the sum of the asphaltenes plus saturates weight percent, divided by the sum of resins and aromatics weight percent. The literature states that if the CII reaches below 0.7, then the asphaltenes can be considered stable; if the CII is greater than 0.9, then the asphaltenes are considered to be unstable (Ashoori et al., 2011). If the asphaltenes are unstable, they are more easily disturbed to precipitate in the solution.

The C2 oil sample showed the lowest viscosity, density, CII, asphaltenes, and resins values, while C1 had the highest asphaltenes and resins contents. C3 has intermediate values for all parameters, relative to C1 and C2. Hence, the microwave responses of the different oils were investigated.

Table 2.1 – Characterization of Crude Oil Samples Used in this Study

Crude Oil Sample	API Gravity, º	Viscosity (cP)	Crude Oil Components (wt %)				Colloidal Instability Index (CII)
			Saturates	1.0309	Resins	Asphaltenes	
C1	6.11	1.00E+07	10.68	0.7422	20.14	40.08	1.0309
C2	17.12	496	30.03	0.8212	15.56	12.57	0.7422
C3	12.09	10100	16.51	37.81	17.1	28.58	0.8212

To introduce the effects of thermal EOR in the form of microwave heating, all individual fractionations and selected SARA mixtures (i.e., polar-polar, polar, and non-polar) were microwaved. A Hamilton Beach 1.1 ft^3 microwave oven of 1,000 W power and 2.45 GHz frequency was used. The masses of the samples were measured before and after microwave heating in order to determine mass loss resulting from the application of the microwaves.

Due to a wide consensus in the literature that asphaltenes are the most polar fraction in crude oil, it was pertinent to first investigate the most polar fraction, followed by the second most polar fraction in resins (Speight, 1991; Nalwaya et al., 1999). Fifty grams of each crude oil sample were subjected to microwave heating for 30 seconds. Due to difficulties with extracting large sample sizes for SARA fractionations, 1 gram of each sample was subjected to the 30 seconds of microwave heating. To observe the impact of polar asphaltenes on microwave efficiency, two asphaltene precipitants (i.e., nC5 and nC7) and an asphaltene dispersant (i.e., toluene) were blended with crude oil at three different weight percentages (i.e., 10%, 20%, and 50%). Two asphaltene precipitants were selected, due to polarity differences in which the nC5 insoluble asphaltenes were less polar than nC7 insoluble asphaltenes. A dispersant in toluene was selected because of its high solvent power compared to the other aromatic solvents (Mitchell & Speight, 1973).

Carefully measuring the masses of the mixtures was important, as was establishing the mixtures' homogeneity. To ensure proper mixing of the crude oil solvent blends, two mixing methods were followed, successfully combating uneven distribution. Before each measurement, each sample was subjected to magnetic stirring at 150 rpm, followed by ultrasonic mixing for 30 minutes. Microwave efficiency was determined through the measurement of the dielectric properties (dielectric constant and loss index) of the bulk crude mixtures before and after microwave exposure. The loss tangent values were calculated through the use of equation 4, which defined the loss tangent as the dielectric index over the dielectric constant.

In this study, the coaxial cable measurement method with a dielectric probe kit was used, due to its efficiency and the access it provided to a wide frequency range (Godio, 2007). The N9923A Field Fox Handheld RF Vector Network Analyzer with probe kit offered the ability to take measurements over a frequency range of 200 MHz to 6 GHz. The temperature tolerance for the analyzer ranged between 0^{o}C and 125^{o}C. The analyzer was calibrated against a shorting block, air, and deionized water, in order to ensure that proper measurements were made.

Specifically, data at 2.45 GHz were taken to study microwave behaviors analogous to the frequency output of the microwaves used during the heating experiments. The probe kit associated with the vector network analyzer took all of the necessary measurements for the dielectric constant and loss index. Since almost all of the measured samples were in liquid state, the probe was fully immersed to ensure accurate readings, with a minimum sample thickness of ~5mm, as per probe specifications. Possible error sources included the calibration process, mechanical agitation, and slight variances in the readings. To prevent such errors, multiple measurements of each data point were taken to ensure the integrity of the results.

The microwave experiments were expected to result in some pyrolysis, which was an indication of thermal cracking in the absence of air (Fernández et al., 2011). Fourier transformed infrared spectroscopy (FTIR) was used to detect chemical structural changes in the initial and microwaved crude oil samples. The Agilent Technologies Cary 630 FTIR was employed for this purpose. The detection of polar function groups was important in determining when polarization occurred from the microwave heating. Common grounds found within crude oil included OH and CH stretches; double carbon bonds; and non-carbon, polar heteroatom compounds including sulfur, nitrogen, and oxygen (Bellamy et al., 1980).

3. RESULTS AND DISCUSSION

The ability of a material to absorb microwaves is a function of the polar nature of the material, so the asphaltenes content of each oil was of particular interest (Haque, 1999). As asphaltenes are reportedly the most polar fraction of the crude oil, they are expected to have the greatest impact on the efficacy of the oil to absorb the incident wave (Bunger and Li, 1982). Therefore, the impact of asphaltenes fraction on microwave efficiency was investigated through blending oil samples with two precipitating agents (nC5 & nC7) at three different weight percentages (10%, 20%, and 50%). NC7 is more polar due to its higher carbon number and precipitates more polar asphaltenes than n-pentane insoluble asphaltenes (Deo & Hanson, 1993). Utilization of nC5 as the agent resulted in more asphaltene quantity, but lower polarity relative to the nC7 asphaltenes (Buckley et al., 2007). **Figure 1** provides the experimentally obtained nC5 & nC7 following the ASTM 2007-11 and ASTM D3279-12 methods. Results from Figure 1 coincided with previous literature knowledge in which less nC7 insoluble asphaltenes are produced when compared to nC5 insoluble asphaltenes (Mitchell and Speight, 1973). While there is a consistency of decreased nC7 insoluble asphaltenes from all three crude oils, the degree of variation is different due to the varying composition of the crude oils. However, it is clearly seen that having the highest amount of nC5 insoluble asphaltenes will also lead to the highest amount of nC7 insoluble asphaltenes.

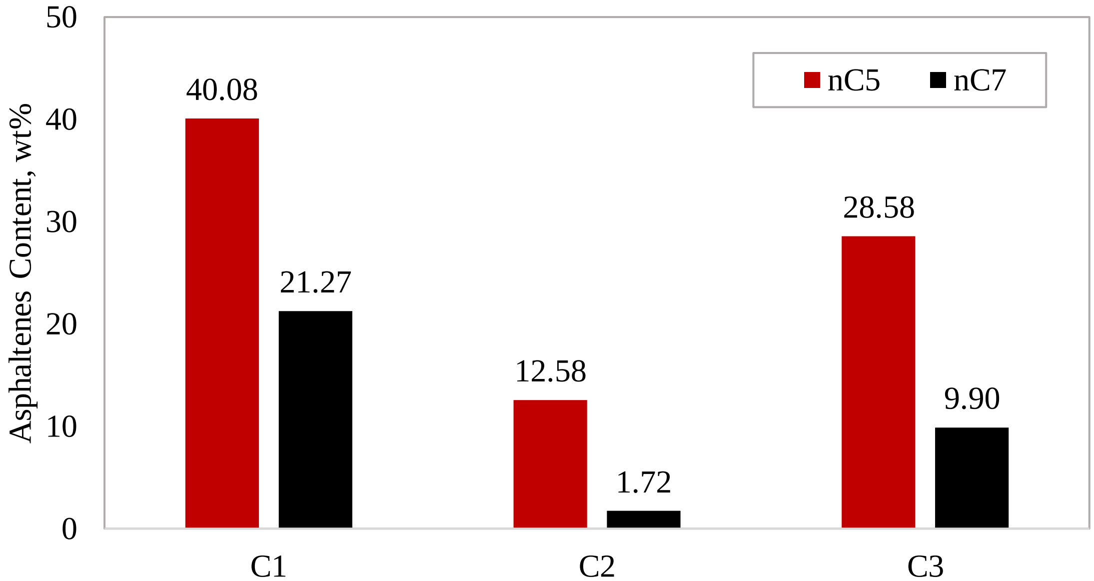


Figure 1—Weight percent of nC5 and nC7 insoluble asphaltenes for all three crude oil samples

Note: nC5 insoluble asphaltenes were separated using the ASTM 2007-11 method while nC7 insoluble asphaltenes were separated using the ASTM D3279-12 method

Table 3.1 – Dielectric Properties of Bulk Crude and Fractionations for Three Crude Oils Before and After Microwave Heating at 2.45 GHz

Parameter	C1											
	Bulk crude		Saturates		Aromatics		Resins		Asph		DAO	
	Initial	MW	Initial	MW	Initial	MW	Initial	MW	Initial	MW	Initial	MW
Dielectric Constant	2.76	2.82	2.35	2.46	3.21	4.35	3.03	3.48	4.78	5.22	2.81	2.56
Dielectric Loss Index	0.05	0.01	0.04	0.05	0.09	0.16	0.04	0.07	0.11	0.14	0.11	0.16
Dielectric Loss Tangent	0.02	0.03	0.02	0.02	0.03	0.04	0.01	0.02	0.02	0.03	0.04	0.06
Penetration Depth	0.69	0.37	0.69	0.57	0.40	0.25	0.77	0.52	0.37	0.31	0.30	0.19
	C2											
	Bulk crude		Saturates		Aromatics		Resins		Asph		DAO	
	Initial	MW	Initial	MW	Initial	MW	Initial	MW	Initial	MW	Initial	MW
Dielectric Constant	2.59	2.72	2.37	2.61	4.04	4.78	2.85	3.38	4.57	5.14	2.64	2.37
Dielectric Loss Index	0.06	0.09	0.02	0.03	0.08	0.09	0.09	0.12	0.17	0.25	0.23	0.33
Dielectric Loss Tangent	0.02	0.03	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.05	0.09	0.14
Penetration Depth	0.57	0.37	1.58	0.92	0.49	0.46	0.35	0.30	0.24	0.18	0.14	0.09
	C3											
	Bulk crude		Saturates		Aromatics		Resins		Asph		DAO	
	Initial	MW	Initial	MW	Initial	MW	Initial	MW	Initial	MW	Initial	MW
Dielectric Constant	2.61	2.78	2.39	2.41	3.42	3.56	3.19	3.68	4.86	5.31	2.84	2.52
Dielectric Loss Index	0.04	0.10	0.03	0.06	0.07	0.10	0.06	0.08	0.10	0.15	0.07	0.14
Dielectric Loss Tangent	0.02	0.03	0.01	0.02	0.02	0.03	0.02	0.02	0.02	0.03	0.02	0.06
Penetration Depth	0.88	0.34	1.06	0.52	0.49	0.36	0.57	0.50	0.42	0.29	0.47	0.22

Note: Deasphalted oil (DAO) consists of saturates, aromatics, and resins in solution, with all of the asphaltenes precipitated out

After determining the asphaltenes content of crude oil, it was important to address the dielectric properties of all of the crude oil samples, including their fractionations. **Table 3.1** consists of the measured dielectric constants and loss indexes, and the calculated loss tangents and penetration depths for all parameters. All measurements were taken within the frequency range of 200 MHz to 6 GHz; the data used in the table were taken at 2.45 GHz. It was observed that the individual polar fractions were relatively more polar than their respective bulk crudes, as depicted by the differences in their dielectric constants.

The asphaltenes were seen to have the greatest potential to store electrical charge, based on the dielectric constant values. When the solid asphaltenes were measured for their dielectric constants alone, their contact with the air masked the true dielectric constant. The molecular structures of asphaltenes are individually unique and do not have the smooth surfaces necessary to obtain proper measurement results from the vector network analyzer. This caused the probe kit to register the asphaltenes as a mixture with air. Therefore, indirect methods were implemented to accurately estimate the polarity of each of the asphaltenes classes, both before and after the microwave treatment. An extrapolation method was used for both nC5 and nC7 insoluble asphaltenes; the results are shown in **Figure A-82**. The utilization of mixing rules enabled the extrapolation of the asphaltenes' relative permittivity response, where the precipitated asphaltenes were mixed at varying weight percentages with a solubilizing agent. Three asphaltene separations were conducted with both nC5 and nC7 as the precipitating agent, with each solid asphaltene's dielectric constant measured with air for the sake of consistency. Deasphalted oil (DAO) was used to solubilize the asphaltenes at discrete weight percent values of 80%, 85%, and 90% to create three data points for the initial mixtures. A fourth point was used with high certainty to validate the data of both initial asphaltenes. A measured value of 2.59 for the initial crude oil dielectric constant was utilized; the oil had 12.57% nC5 and 1.72% nC7 insoluble asphaltenes (Punase and Hascakir, 2017). The 80%, 85%, and 90% DAO mixtures were then microwaved for 30 seconds, and the dielectric constants plotted for the microwaved data. A linear extrapolation was used to obtain the asphaltenes' dielectric constant value. The results showed that the microwave-generated asphaltenes had a higher dielectric constant. As discussed above, asphaltenes are the most polar fraction of the crude oil. Therefore, we expected to see marketable increases in the asphaltenes' ability to store electrical charge. The nC7 insoluble asphaltenes were more polar, as a function of the higher dielectric constant value.

Quantitative analysis of the extrapolation method depicted in **Figure A-82** can be explained through dielectric constant results. The asphaltenes data were directly taken from the results (the y-intercept values in the figure,) while the DAO values were obtained from the data reported for the specific crude oil. The initial asphaltenes dielectric constants were noticeably higher than the DAO, suggesting a substantial difference in the relative polarities difference between the two components. However, when we compare the dielectric constants for the crude oil and DAO, we noticed that the DAO had a higher relative polarity. This finding further suggests that when the asphaltenes are separated from the solution, freeing the resins will increase the relative polarity of the mixture. Furthermore, after comparing the nC5 and nC7 asphaltenes, a small increase in dielectric constant was found, suggesting that the polarity of the solvent used to precipitate the asphaltenes had a much lower impact than did the actual microwaving heating of the asphaltenes.

The asphaltenes fraction was identified as having the greatest potential to absorb microwaves, a conclusion that is corroborated in **Figure A-82** through **Figure A-84**. Upon comparison of the resins and asphaltenes fractions, it became clear that there was a greater differential increase in the dielectric constant of the asphaltenes after the microwave treatment. The magnitude of the dielectric constant after the microwave treatment indicated the achievement of an increased polarity for both the resins and the asphaltenes, through the addition of the microwave heating. However, the larger difference in the asphaltenes post- microwaving was associated with an increased capability to absorb more microwave energy relative to the resins. This validated the literary arguing for asphaltenes as the most polar component of crude oil; they will therefore preferentially absorb microwave energy relative to the other crude oil fractions.

Furthermore, determination of the crude oil's polarity was not seen to have an additive procedure, where certain fractions' dielectric constants cancel each other out. This was further observed when the initial dielectric constant of the DAO was greater than that of crude oil. We hypothesize that if the asphaltenes are completely removed from the solution, the resins will be freed, increasing the relative polarity of the resins and the overall mixture. While aromatics are defined in literature as non-polar, the aromatics fraction showed a relative polarity compared to the crude oil, and could play a role in controlling the crude oil's microwave efficiency. Microwave heating altered the polarity of the individual fractions, as seen in the FTIR results (**Figures A-94 to A-111**). Although saturates and aromatics (i.e., the non-polar fractions), lost components during the microwave heating, some of those lost constituents may have been converted to resins, describing the increase in the dielectric constant. The amount of resins was seen to increase after the microwave heating; this was caused by the addition of OH bonds, mostly in the form of water. The amount of asphaltenes also increased post-microwaving, increasing the dielectric constant. This can mainly be attributed to the polarity of the heteroatoms. In terms of absorption through the loss tangent, it was consistently found that the asphaltenes fraction had the highest efficacy for absorbing microwaves, followed by the other polar fraction in the resins. However, deasphalted oil was found to consistently offer the greatest loss tangent percentage increase, as compared to post-microwave asphaltenes. FTIR results of the deasphalted oil shows that light components have been lost. This suggests that freed resins might interact with the polar sites of the aromatics: namely, the polar heteroatoms. By this hypothesis, crude oil samples with larger concentrations of heteroatoms will generate more heat when interacting with freed resins. Thus, while determining the contribution of each fraction is important, the dielectric behavior of bulk crude oil mixtures is also essential to gauging the mutual interactions between polar fractions. FTIR results varied for each crude oil, suggesting that microwave heating reacts differently to all three samles.

Introducing energy in the form of the microwave irradiation essentially adds energy to the system that is absorbed by the more polar components of the crude oil (Thostenson and Chou, 1999). The magnitude of the energy absorption is a direct function of the polarity of the sample where more polar components will preferentially absorb more energy. **Figure 2** suggests the presence of microwave pyrolysis through the increased asphaltenes content post microwave heating.

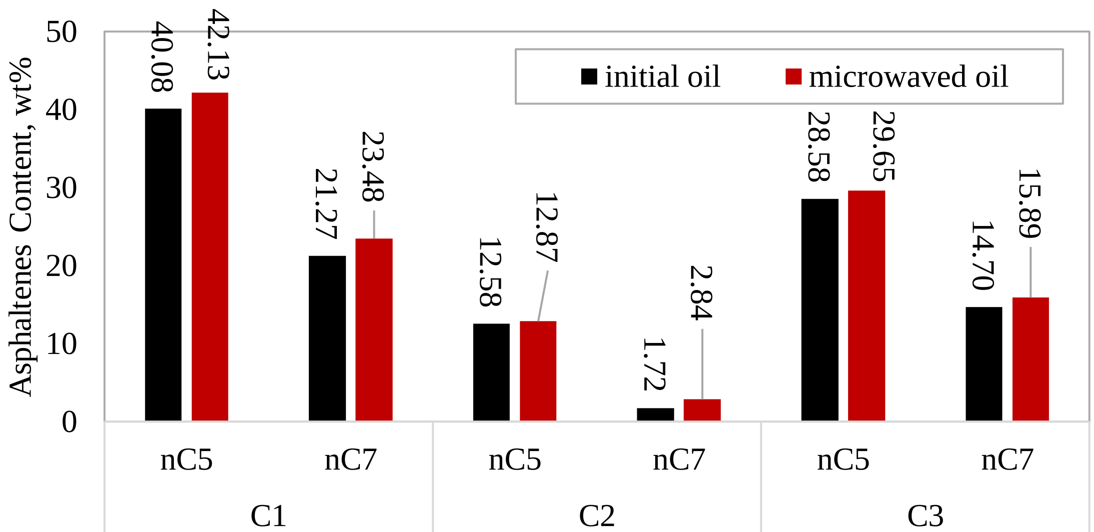


Figure 2— Weight percent of nC5 and nC7 insoluble asphaltenes both before and after microwave exposure for 3 minutes of all crude oil samples

Next, it was noted that for all samples there is an increased asphaltenes content post microwave heating. Mass loss for all samples post microwave are recorded, from which the percentages range from 0.06% to 0.17% (**Figure A-112**). These results further suggest the presence of microwave pyrolysis, which is defined as the thermal decomposition of material at elevated temperatures in the absence of oxygen. One of the byproducts from microwave pyrolysis is asphaltenes, which explains all microwaved samples (Bilali et al., 2005). Furthermore, the degree of increase from the more polar nC7 insoluble asphaltenes is higher than nC5 insoluble asphaltenes. Therefore, both the amount of asphaltenes and the polarity of the asphaltenes can contribute to the overall microwave effectiveness.

To better understand the role of asphaltenes on microwave effectiveness, crude oil samples were blended with two asphaltenes precipitants (nC5 & nC7) as well as an asphaltene dispersant (toluene). Results are examined through measurements of dielectric properties for all three crude oils. Note that while the use of nC5 and nC7 is targeted to precipitate asphaltenes out of solution, toluene is used to disperse asphaltenes in solution. The difference in oil compositions can give insight into dielectric property response targeting the effectiveness of asphaltenes.

Figure 3 shows the dielectric constant comparisons for C1 crude oil blends with the added solvent (nC5, nC7, and toluene) at discrete weight percentages (10%, 20%, and 50%).

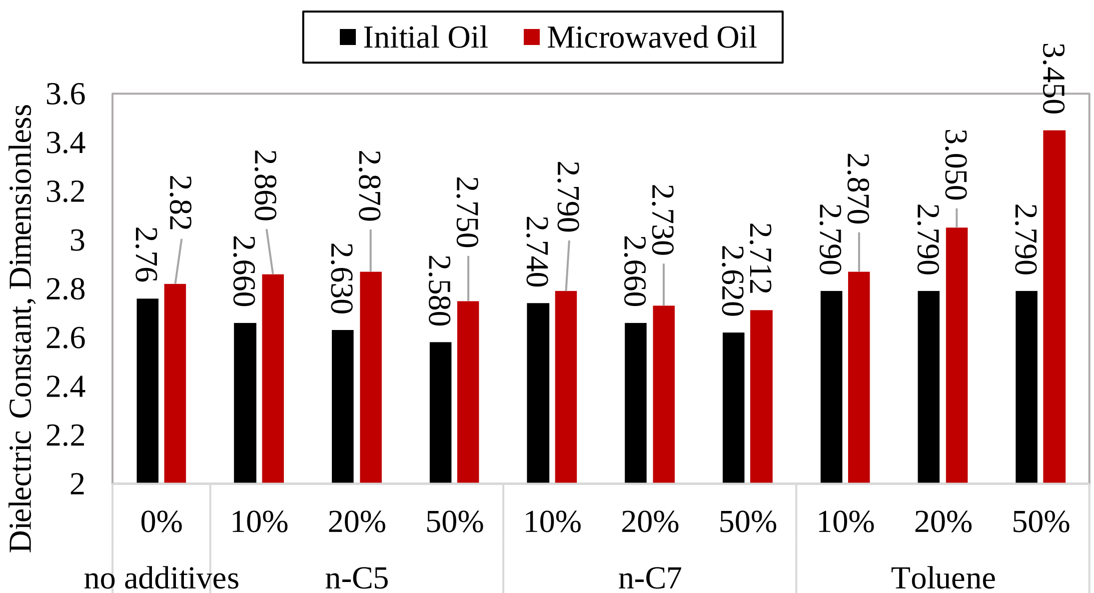


Figure 3— Dielectric Constant of C1 crude oil blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentration before and after 3 minute microwave exposure at 2.45 GHz
Note: Asphaltenes precipitated at 50% for nC5 was 11.2%, nC7 asphaltenes at 50% was 5.67%, while the bulk crude contains 40.08%

For crude oil C1 (Figure 3), the dielectric constant from the initial oil sample to the 10% nC5 mixture experiences a decrease in the relative polarity. The increased addition of precipitants further decreases the relative polarity of the oil blend. This trend can be explained through the composition properties of the crude oil C1. First, this sample contains the largest weight percentage of asphaltenes present, as well as the highest asphaltenes-to-resins ratio. Specifically, the ratio between asphaltenes and resins can contribute directly to the overall stability of the crude oil in relation to the colloidal instability index (CII) (Marques et al., 2012).

Although the weight percentage of asphaltenes in the bulk could contribute to dielectric constant results, the stability of the asphaltenes in solution is very important to the behavior of the mixtures. We define this stability by definition of the colloidal instability index (CII), which is the summation of asphaltenes plus saturates weight percentage divided by the summation of resins and aromatics weight percentage. In literature, if the CII reaches below 0.7 then the asphaltenes are considered stable, while if the CII is greater than 0.9 then asphaltenes are considered to be unstable (Ashoori et al., 2011). If the asphaltenes are unstable, they are more easily disturbed to precipitate in solution.

From the previous definition of the CII, we can observe that only C1 oil sample has unstable asphaltenes with 1.031 CII value (Table 2.1). In addition, the high CII value of C1 crude oil has around a 20% weight difference of asphaltenes over resins, signifying a large amount of free asphaltenes that may not be adsorbed by resins. Combining previous reasoning, the relative decrease of dielectric constant through addition of both precipitants (nC5 and nC7) is caused mostly by the precipitation of free asphaltenes out of solution.

While the decreasing trend for addition of precipitant solvent (nC5 and nC7) to crude oil 1 is consistent, a direct relationship between the exact weight percentages added versus the dielectric constant is non-linear and complex.

However, the addition of toluene as an asphaltene dispersant solvent showed very different results from the precipitant blends. Although the initial toluene blends did not show a change in the dielectric constant, post microwave blends resulted in a linear trend with respect to concentration change (y = 1.3571x + 2.7686), where y = ε', the dielectric constant, and x = toluene concentration. Thus, toluene is seen to increase the microwave efficiency through increase of the dielectric constant.

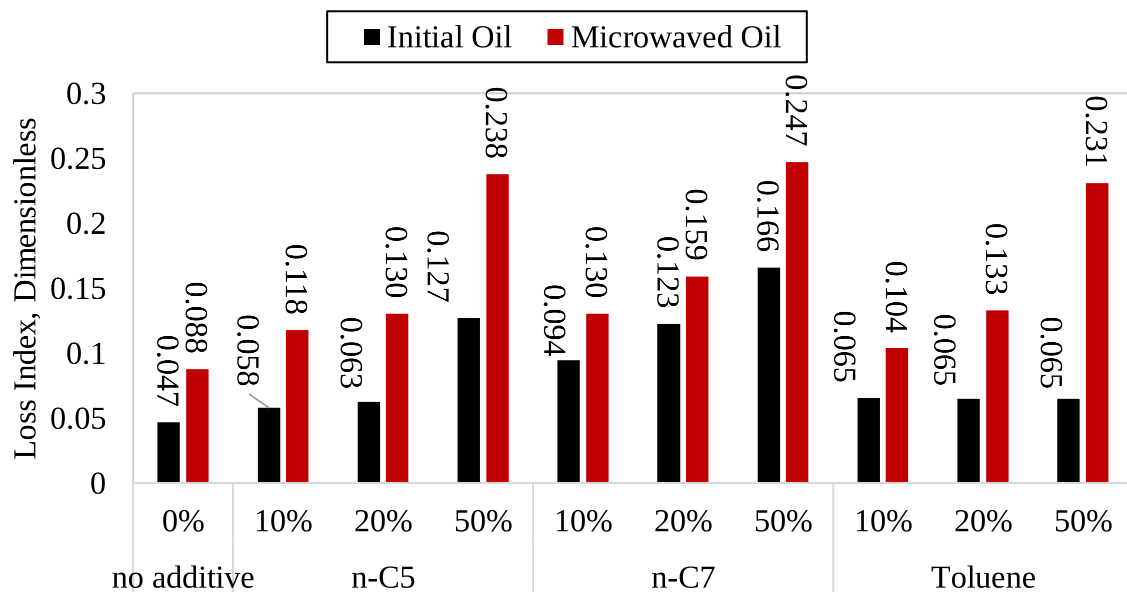


Figure 4— Dielectric loss index of C1 crude oil blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentration before and after 3 minute microwave exposure at 2.45 GHz

Loss Index values in **Figure 4** were measured, from which this variable represents a material's ability to generate heat (Zhu, 2006). It is shown that the precipitation of the polar asphaltenes will directly increase the capacity to generate heat, with the more polar nC7 insoluble asphaltenes generating higher heat relative to nC5 insoluble asphaltenes. This suggests that dispersed asphaltenes and resins together creates a greater contribution to the loss index when compared to the excess asphaltenes alone. Toluene mixtures prior to microwave heating does not increase the bulk mixture's ability to generate more heat, as minimal amount of toluene was needed to disperse the crude oil blends. However, increasing this polar solvent's concentration post microwave will enhance the overall heat generation, possibly due to the increased temperature rise which may yield additional asphaltenes in the presence of microwave pyrolysis effects.

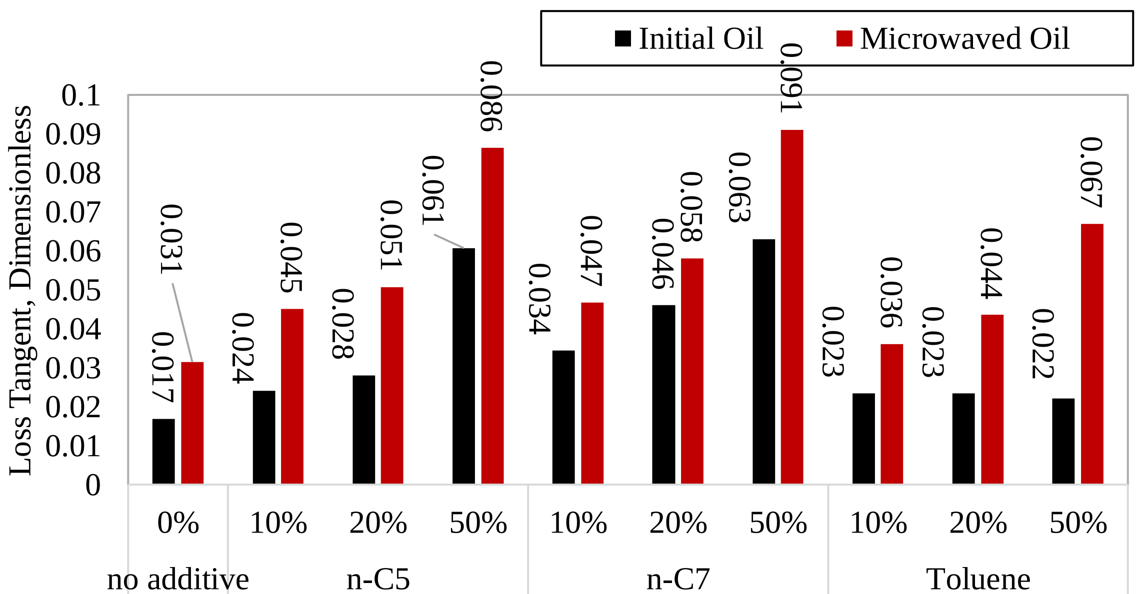


Figure 5— Dielectric loss tangent of C1 crude oil blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentration before and after 3 minute microwave exposure at 2.45 GHz

The loss tangent values calculated in **Figure 5** represent the blend's ability to absorb microwave energy by applying equation 4. It is a quantitative representation of the efficacy of the material to absorb microwave energy where larger values correspond to better microwave energy storage. This frequency dependent variable is defined as the dielectric loss index divided by the dielectric constant (equation 4). Thus, the trend of the loss tangent should exactly follow that of the loss index from Figure 4. It is observed that precipitating asphaltenes enhances the microwave absorption capacity, since nC5 and nC7 achieved higher loss tangent than toluene mixtures. It can be concluded that asphaltene precipitants may enhance microwave absorption for this specific crude oil (C1) more than the asphaltene dispersant. This can be due to the polar-polar interaction of resins with asphaltenes. This interaction might cancel the overall polarity of the crude oil C1. Elimination of asphaltenes may increase the presence of resins to increase the polarity of the crude oil. Initial toluene mixtures are seen to remain constant because the composition of the crude oil remains constant. However, when heat is introduced from microwave heating post dispersion, the increased homogenization of asphaltenes in solution creates higher zones for preferential heating.

When microwaves are transmitted through a vacuum, the wave would theoretically propagate to infinity, but since there is polarity in all oil samples there will be an attenuation factor that will decrease the penetration depth, with results reported in **Figure 6**. Thus, penetration depth is an important parameter to understand in the field scale as it directly pertains to the stimulated reservoir volume. This parameter was calculated by using equation 3, and it is important to note that the penetration depth is not a dielectric property.

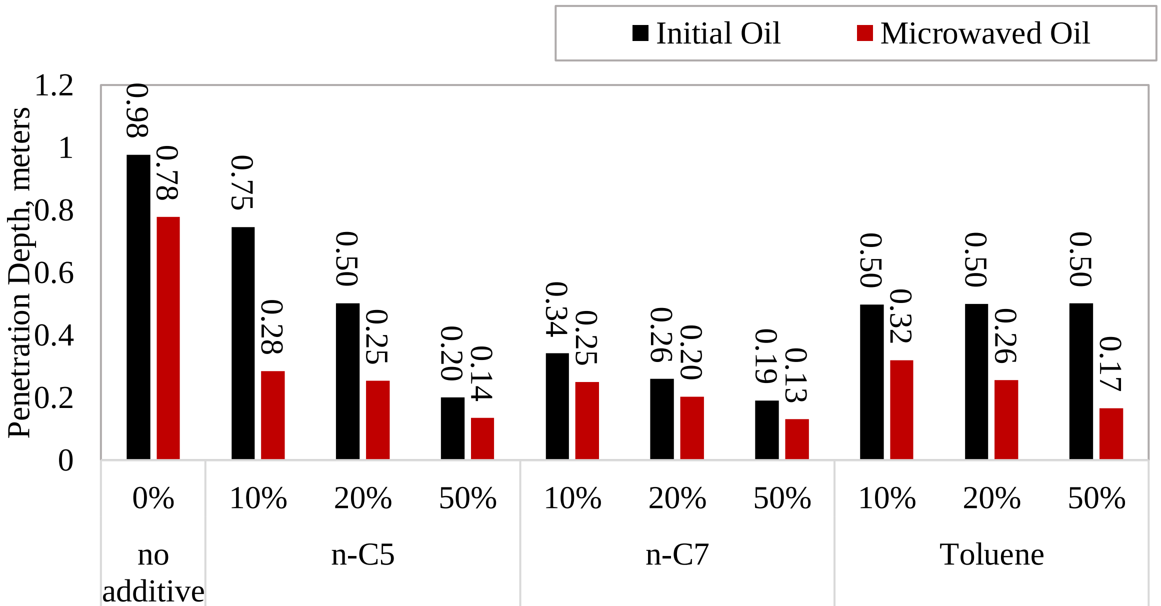


Figure 6— Penetration Depth of C1 crude oil blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentration before and after 3 minute microwave exposure at 2.45 GHz

Loss tangent is the most important variable when determining penetration depth, for when the absorption capacity increases the penetration depth will decrease as a result. Thus, the results seen in **Figure 6** that shows all penetration depths achieved are directly opposite to those of Figure 5. The desired goal of the mixtures is to obtain the least penetration depth since it will mean that the bulk crude mixtures have absorbed most of the microwave energy. Consequently, it is seen that the precipitation of asphaltenes will cause a decrease in penetration depth, with the more polar nC7 mixtures obtaining the lowest penetration depths. The addition of dispersants will not alter the initial penetration depths while the introduction of the microwave heating will noticeably decrease the penetration depth.

Similar analyses were also conducted on C2. Note that crude oil C2 has the least weight percentage of asphaltenes and resins, along with the most stable asphaltenes, from the three samples, due to the lowest CII values in Table 2.1. Thus, one should expect the result trends of the oil mixtures for C2 to react differently from C1.

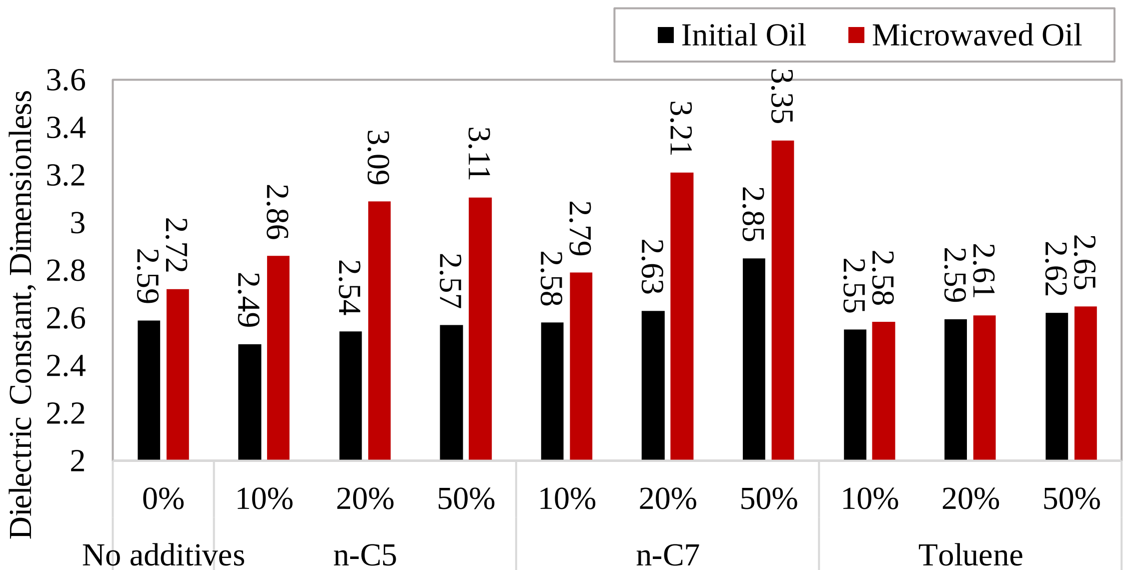


Figure 7— Dielectric constant of crude oil C2 blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentration before and after 3 minute microwave exposure at 2.45 GHz
Note: Asphaltenes precipitated at 50% for nC5 was 2.12%, at 50% for nC7 was 0.37%, while the bulk crude contains 12.58%

Figure 7 displays the dielectric constant measurements of all nine mixtures for both the initial and the post microwave cases. Increased concentration of precipitant solvents increased the relative dielectric constant of the blends, the exact opposite of crude oil C1. To discuss, we must observe differences in the composition of crude oil C2. This oil sample has the lowest weight percentage of resins and asphaltenes, and the most stable asphaltenes out of all three samples. Thus, the fundamental principles behind the relative polarity increase should not be dependent on asphaltene precipitation alone, but more on the polar-polar interactions of the crude oil blends. Resins and asphaltenes are defined as the polar fractions of crude oil. Out of all possible polar-polar interactions within crude oil, resins-asphaltenes interactions are preferred over resins-resins and asphaltenes-asphaltenes (Speight, 2004). Thus, one can make the assumption that most of the resins are adsorbed onto the asphaltenes surfaces when dispersed in solution. When asphaltenes precipitate as a function of added precipitant solvent (nC5, nC7), it can be hypothesized that resins are no longer adsorbed to the asphaltenes surface and become free. The dielectric constant may increase as a function of freed resins for crude oil C2, which contained stable asphaltenes. Toluene mixtures remained consistent with crude oil C1 in that the addition of the dispersant did not experience a large change in the dielectric constant. The composition of the crude oil remains constant and should not experience a change in relative polarity.

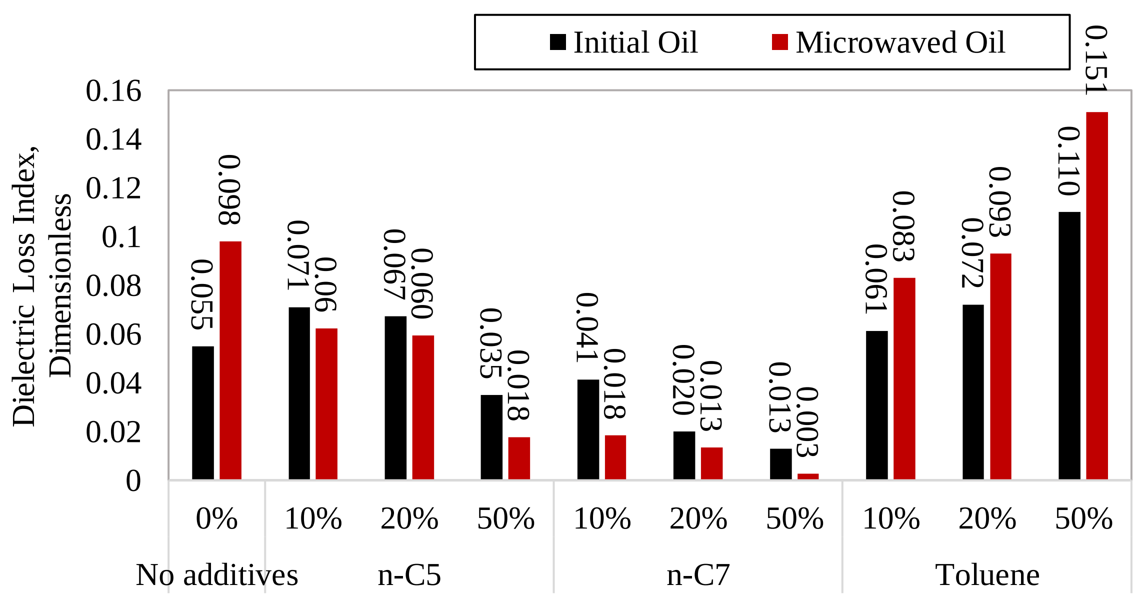


Figure 8— Dielectric loss index of crude oil C2 blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentration before and after 3 minute microwave exposure at 2.45 GHz

Again, dielectric properties in terms of heat generation have been investigated through dielectric loss index measurements, from which results are given in **Figure 8**. Results from Figure 8 are directly related to the loss tangent trends as seen in Figure 9. It is seen that the addition of precipitants will greatly hinder the oil's capacity to generate heat, with nC7 mixtures performing much worse than nC5 mixtures. In this scenario, the dielectric loss index decreases as a function of the proposed idea of freed resins. Asphaltenes precipitated out of solution are seen as detrimental to the heat generation capacity of crude oil C2. This may suggest that resins adsorbed to asphaltenes present a greater contribution to the loss index when compared to stand-alone fractions in resins and asphaltenes. Furthermore, this may suggest that the freed resins are also interacting with the polar sites of aromatics, namely the heteroatoms. The polar-polar interactions in the absence of asphaltenes may cause a further cancellation of polarity, decreasing the crude oil blend's ability to generate heat. Toluene mixtures, however, respond very favorably as the greatest increase in dielectric loss index is seen in dispersant mixtures. The additional polar solvent concentration will increase the microwave's efficacy to generate more heat.

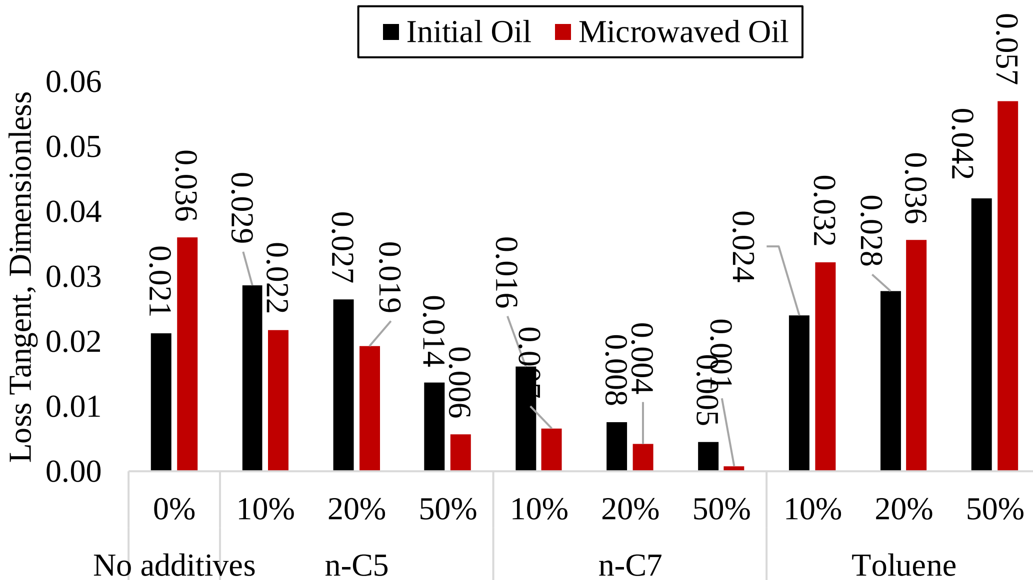


Figure 9— Loss tangent of crude oil C2 blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentration before and after 3 minute microwave exposure at 2.45GHz

The parameter of loss tangent is mathematically defined as the ratio of the loss index to the dielectric constant. **Figure 9** shows the loss tangent values of all crude oil C2 mixtures. Following definition of the loss tangent similarly for crude oil C1, the loss tangent trends should be related directly to the loss index values in Figure 8. Precipitating asphaltenes out of solution decreases the crude oil's efficacy to absorb microwave energy. While relative polarity can be increased through the freeing of resins, it is more detrimental when the crude oil loses over 75% of its loss tangent value when blended with 50% nC7. Dispersant blends, on the other hand, do not change the composition of the crude oil and enhance the initial oil in solution in its ability to absorb microwaves more than twofold by adding 50% of toluene. Once again, while the penetration depth is not a dielectric property, it is important to calculate this parameter for the field scale considerations, as presented in **Figure 10**.

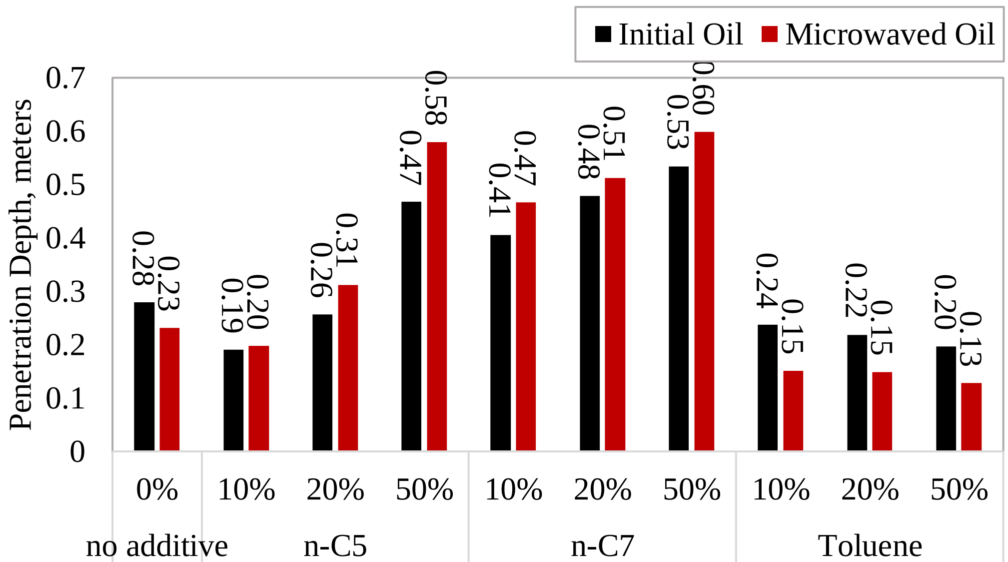


Figure 10— Penetration depths of crude oil C2 blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentration before and after 3 minute microwave exposure at 2.45 GHz

Figure 10 shows that, with the introduction of the microwave into dispersant mixtures, a decrease of penetration depth is consistently achieved. Precipitated asphaltenes, on the other hand, increases penetration depth, which induces larger energy losses and poorer reception of microwave absorption. More polar precipitants in nC7 further increase the penetration depth. When conceptualizing the importance of all dielectric properties through penetration depth, it is clear that the loss tangent is the most important variable, followed by the loss index, and lastly by the dielectric constant. There is less need to optimize the electrical storage charge if there is suboptimal heat generation and absorption.

Lastly, oil sample C3 contains intermediate asphaltenes and resins (Table 2.1), and has relatively stable asphaltenes when compared to C1 (Table 2.1). All mixtures shown in **Figure 11** have the same ratios as the previous oil samples from C1 and C2.

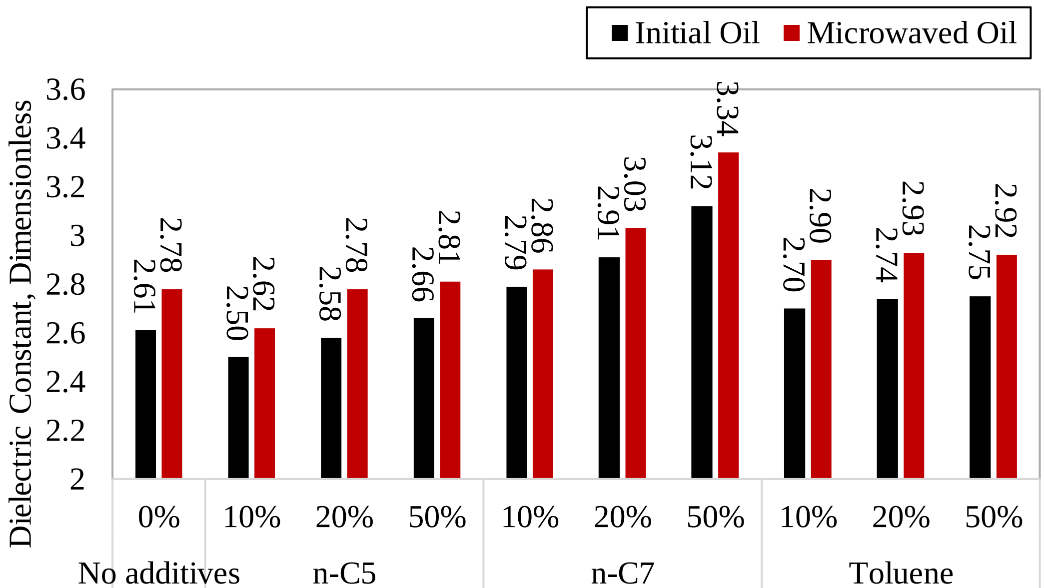


Figure 11— Dielectric constant of C3 crude oil blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentration before and after 3 minute microwave exposure at 2.45 GHz
Note: Asphaltenes precipitated at 50% for nC5 was 5.45%, 50% for nC7 was 2.68%, while the bulk crude contains 28.58%

Precipitant mixtures followed the behavior seen from Figure 7 for oil C2, where the dielectric increase can be seen as a function of increased asphaltenes precipitated. Although the initial value decreased, resins are being freed from the polar asphaltene precipitated, resulting in an increase to the dielectric constant as a function of precipitated asphaltenes. As a result, nC7 as a more polar asphaltene precipitant is seen to have greater dielectric constant values that align with Figure 8 results. The dielectric constant did not increase as a function of increased dispersed toluene, which still suggests that small amounts of toluene can assist in stabilizing most asphaltenes in the crude oil. Note that toluene has a very high solvent power relative to other dispersant solvents (Mitchell and Speight, 1973). Loss index values were also observed in Figure 12.

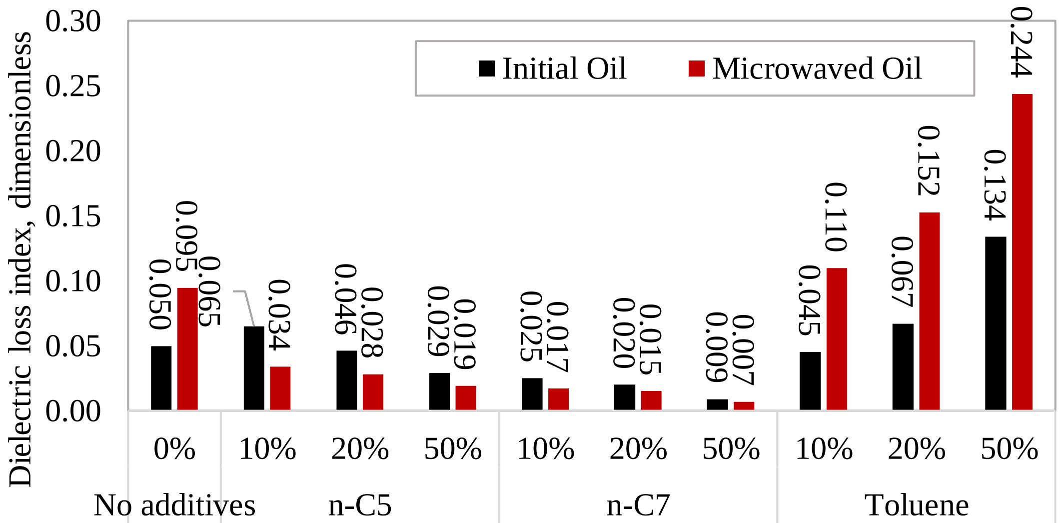


Figure 12— Dielectric loss index of C3 crude oil blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentration before and after 3 minute microwave exposure at 2.45 GHz

Again, by definition this variable is measured along with the dielectric constant. Thus, the same trends for the loss tangent from Figure 11 are apparent here. Here it is seen that the addition of precipitant mixtures will decrease the oil sample's capacity to create heat. The cause behind the decrease can be explained in the same manner as the loss index results of crude oil C2. Freed resins from asphaltene precipitation prefer to experience polar-polar interactions with the polar heteroatoms of the aromatics, decreasing overall polarity and the ability to generate heat. The large increase in toluene blend loss index post microwave heating may once again be attributed to the microwave pyrolysis effect where additional asphaltenes are produced. An optimal toluene concentration can be found to surpass the precipitant's maximum dielectric loss index, similar to the loss tangent results seen in Figure 12.

Similarly, the loss tangent values are investigated to determine the oil mixtures' propensity to absorb microwave energy, shown in **Figure 13**.

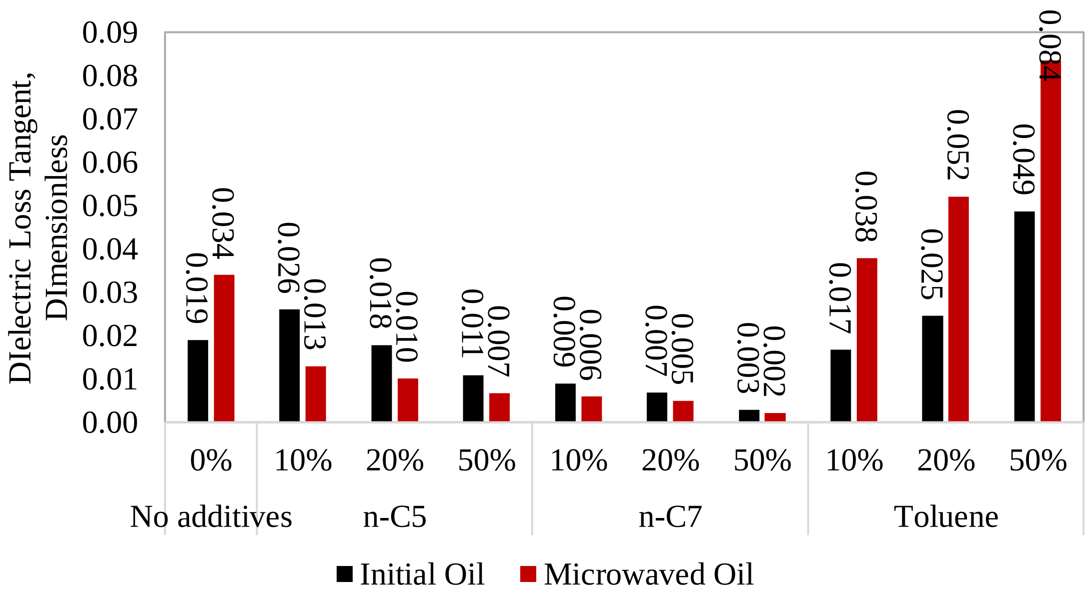


Figure 13— Dielectric loss tangent of C3 crude oil blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentration before and after 3 minute microwave exposure at 2.45 GHz

Initially, it can be seen that the loss tangent increases with the addition of precipitants, but with its efficacy drastically decreasing with increased concentration. Once again, the variable of loss tangent described the material's ability to absorb microwave energy. Additionally, the increase in toluene assists the increased heat generation from the microwaving process. While the only increasing trend is through the use of dispersants for crude oil C3, the addition of 50% toluene does not surpass the loss tangent of low-concentration precipitant mixtures. As a result, nC5 reached the best effectiveness of heat dissipation while carrying asphaltenes in trace amounts.

Penetration depth values of C3 are calculated after determination of dielectric properties, shown in **Figure 14**.

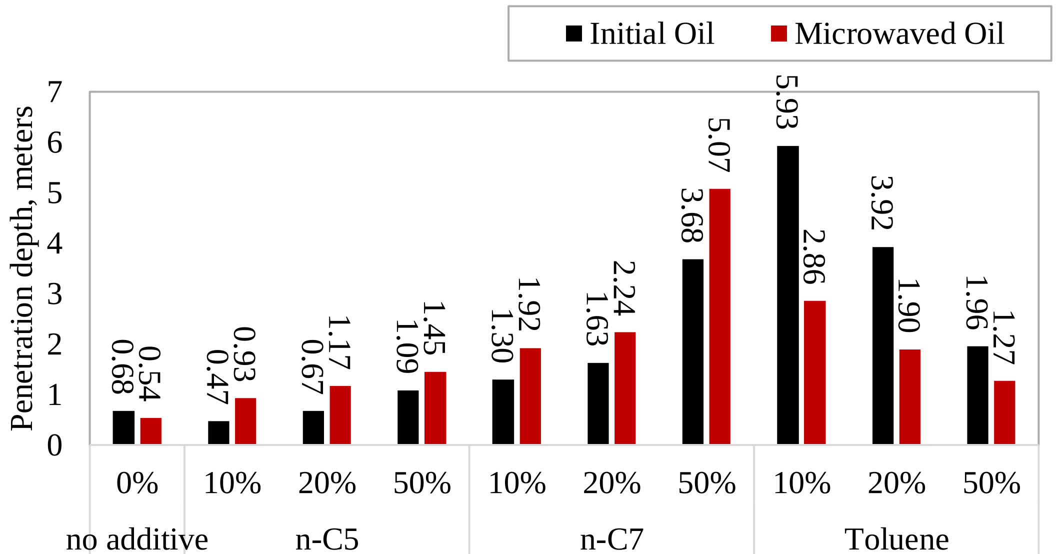


Figure 14— Penetration Depth of C3 crude oil blends with nC5, nC7, and toluene at 10%, 20%, and 50% weight concentration before and after 3 minute microwave exposure at 2.45 GHz

The addition of precipitants increased the penetration depths as it is inversely related to the absorption of the microwave energy. Since the loss tangent is the most important parameter for penetration depth, a much higher dispersant concentration is needed to achieve the same relative penetration depths as C1 and C2.

Although observations and hypotheses were produced from individual crude oil samples, it was also important to find correlations between all three samples for all dielectric properties. Dielectric constant results split into two trends in accordance to asphaltenes stability, so no common ground was found between all three crude oils. However, the dispersant effect on all three crude oils were found to share similar correlations. Initial toluene mixtures were seen to remain relatively constant for all three crude oils, while strong correlations can be drawn for microwaved samples, shown in **Figure 15.**

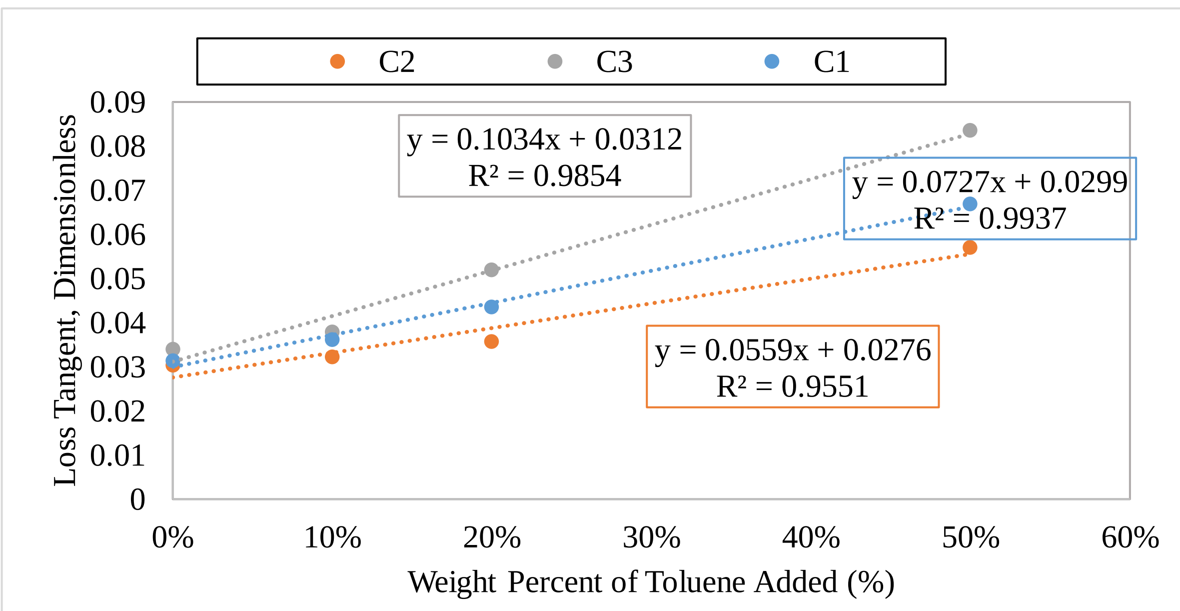


Figure 15— Correlations on the contribution of toluene for all crude oil samples before microwave at 2.45 GHz

Although the innate stability of the asphaltenes was different for each of the three crude oils, the addition of toluene, in conjunction with the microwave heating, produced the same increase trend, but to varying degrees of effectiveness. The magnitude of the toluene contribution can be seen from several angles. First, the individual dielectric constants of the resins and asphaltenes were seen to have a direct effect on toluene's effectiveness. That is, C3 had the most polar resins and asphaltenes, while C2 had the least. The increase of temperature may increase the weight percent of asphaltenes in solution, directly increasing the loss tangent. The interaction between the two polar fractions in the solution may be the key to optimizing absorption in the system.

Mutual interactions between resins and asphaltenes were investigated as it has been seen to affect dielectric properties for various crude oils. Resins are known as a peptizer to asphaltenes (Asomaning, 2003). Hence, resins interaction with asphaltenes was also investigated for all three crude oils. It was aimed to see if the resins and asphaltenes polarity cancels or is additive in solution. Thus, resins and asphaltenes were blended by considering the exact ratios of resins and asphaltenes in crude oil and these mixtures were exposed to microwave irradiation for 3 minutes. Dielectric properties of these mixtures before and after microwave heating are given in **Table 3.2.**

Table 3.2 – Dielectric Properties of Resins and Asphaltenes Mixtures for All Three Crude Oils Before and After Microwave Heating at 2.45 GHz

	C1		C2		C3	
	Initial	Microwaved	Initial	Microwaved	Initial	Microwaved
Dielectric Constant	3.310	4.510	2.810	4.230	3.420	4.640
Loss Index	0.043	0.132	0.068	0.168	0.054	0.154
Loss Tangent	0.013	0.029	0.024	0.040	0.016	0.033
Penetration Depth	1.534	0.309	0.482	0.238	0.663	0.272

Although the three crude oil samples all have different ratios of resins to asphaltenes, the overall dielectric constant of resins and asphaltenes blends decreased when compared to their individual dielectric constant. Asphaltenes in the reservoir under thermodynamic equilibrium are dispersed in solution as a result of interactions with the other fractions of crude oil (Speight et. al., 1985). Asphaltene dielectric properties are therefore not mutually exclusive, but instead are a function of the interaction of the various components of the crude oil.

Resins are considered to be the second most polar fraction of the bulk oil and will accordingly interact with the asphaltenes, which are also polar (Speight, 1991). The mixture provided will account for the *in-situ* interaction between the two most polar components of the crude oil where the greatest microwave energy absorption would occur, which is evidenced by the largest increase in dielectric constant post microwave heating. The initial mixture dielectric constant results closely resemble the dielectric constant of resins alone. This seems to suggest that a local cancellation of polarity is occurring between the resins and asphaltenes. From literature it was found that when resins and asphaltenes are together, resin-asphaltene interactions are preferred over asphaltene-asphaltene interactions (Speight, 2014).

It was observed that the mixture loss index values were less than those of the individual resins and asphaltenes. Polarity cancellation was also seen to affect the loss index, where there was a consistently decreasing effect for all three crude oils. However, when microwaved, the loss index experienced a significant increase, though not surpassing that of the asphaltenes alone. The ranks of magnitudes for the loss index may be directly related to the resins-to-asphaltenes ratio, with the highest ratio generating the greatest heat. The opposite could be seen in the loss tangent values, where the highest asphaltenes-to-resins ratio generated the greatest efficacy in terms of heat generation.

The last factor to investigate was the effect of temperature on the microwave response of all three bulk samples. Although localized behavior of various crude oil reacted differently according to asphaltenes solubility defined by the colloidal instability index values, the global response of all three heavy crude oils samples to microwave has been consistent. That is, both the dielectric constant and loss tangent of the bulk crude have increased post microwave heating. The introduction of the microwave for three minutes introduces a heating component that is similarly experienced for all three oils and blends. Therefore, the temperature dependency of the dielectric properties was investigated for samples C1, C2, and C3 (**Figure 16**).

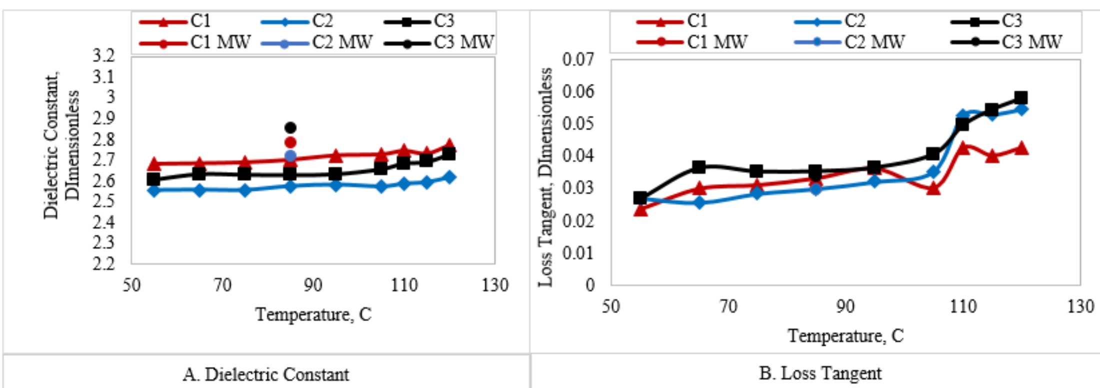


Figure 16 – Dielectric Constant and Loss Tangent of crude oils C1, C2 and C3 at varying temperatures

In Figure 16, it has been confirmed that the heavy oil's absorption capacity is increased when exposed to higher temperatures. Therefore, the absorption capacity of the oil is not only dependent upon the composition of the crude oil but also upon the temperature of the sample. Composition of the crude oil can change the loss tangent response irrespective of the temperature increase. Furthermore, the percent difference from conventional to microwaved data was calculated for dielectric constant and loss tangent values of all three crude oils, which are shown in table 3.3.

Table 3.3 – Crude oil Properties with Correlation to Temperature Dependence Results for Dielectric Properties

Crude Oil Samples	API gravity (°)	Viscosity (cP)	Crude Oil Components (wt %)				Colloidal instability index	initial		final		Percent difference	
			Saturates	Aromatics	Resins	Asphaltenes		ε′	tan δ	ε′	tan δ	ε′	tan δ
C1	6.11	1.00E+07	10.68	29.1	20.14	40.08	1.0309	2.66	0.0213	2.72	0.0365	2.26%	71.36%
C3	12.09	10100	16.51	37.81	17.1	28.58	0.7422	2.61	0.0235	2.65	0.0512	1.53%	117.87%
C2	17.12	496	30.03	41.84	15.56	12.57	0.8212	2.56	0.0246	2.59	0.0545	1.17%	121.54%

Results of table 3.3 shows a reorientation of the results to establish a correlation between API, viscosity, CII, and the change in dielectric constant and loss tangent percentage performance. This correlation may be used with additional oils to promote a strong relationship between the four major parameters.

Oil samples in table 3.3 with low saturates and aromatics correlate to having the lowest API while having the highest weight percentages of polar asphaltenes and resins correlate to high viscosity. The difference values of dielectric constant and loss tangent are inversely related. That is, low API gravity, high viscosity, low saturates and aromatics, and high resins and asphaltenes contribute to a greater increase of dielectric constant (2.26%). The opposite can be said for the increase of the loss tangent. Changing the temperature will significantly alter loss tangent values (121.54%), which is seen to have enormous benefits of reducing viscosity.

The results establish that oil candidacy as a microwave absorber under the influence of temperature, to some extent, can be estimated by comparative utilization of physical properties for crude oils with their respective change to their dielectric properties. Correlations were reached between such parameters to observe the most favorable conditions for the largest absorption capacity difference. CII values are not great indicators for the dielectric constant results of individual crude oils. This comparison does not incorporate the physical properties of crude oils. Thus, the CII values must be used in conjunction with more meaningful parameters such as API and viscosity to better represent and visualize the effects of the oil phase in a thermally dynamic system.

Although conventional heating data was useful in establishing temperature dependence for bulk crude oils, microwave heating data must also be used to compare performances.

Table 3.4 – Crude oil Properties with Correlation to Microwave Heating Results for Dielectric Properties

Crude Oil Samples	API gravity (°)	Viscosity (cP)	Crude Oil Components (wt %)				Colloidal instability index	initial		final		Percent difference	
			Saturates	Aromatics	Resins	Asphaltenes		ε′	tan δ	ε′	tan δ	ε′	tan δ
C1	6.11	1.00E+07	10.68	29.1	20.14	40.08	1.0309	2.76	0.017	2.82	0.031	2.17%	82.35%
C3	12.09	10100	16.51	37.81	17.1	28.58	0.7422	2.61	0.018	2.78	0.034	6.51%	88.89%
C2	17.12	496	30.03	41.84	15.56	12.57	0.8212	2.59	0.021	2.72	0.036	5.02%	71.43%

Table 3.4 describes the dielectric constant behavior of initial versus 3 minutes of microwave for all three crude oils. It's important to note that although the trends remain relatively consistent, the performance values are different when compared to results of

table 3.3. Absorption increases are found to be around 39% in difference, in favor of the conventional heating results. Several suggestions can be made to increase the microwave performance. First, the heating time may be increased to further increase the sample temperature, which will results in a greater difference in the dielectric behavior. Secondly, dielectric properties are very sensitive to frequency as well, and all of the experimental data were taken at one discrete frequency of 2.45 GHz. Thus, future experiments can be taken at different frequencies to find the optimal increase in either dielectric constant or loss tangent.

4. CONCLUSIONS

The investigation of three crude oils was conducted on the basis of maximizing microwave effectiveness, with the focus being on absorption. Contribution of polarity in the individual fractionations was examined through dielectric constant measurements. The role of polar asphaltenes in microwave efficiency was determined through bulk crude oil mixtures with two precipitants and a dispersant. Mutual interactions within the crude oil fractions were investigated, with concentrated efforts on the polar-polar interactions between resins and asphaltenes. Experimental results were focused on explaining the contribution of certain parameters in maximizing absorption.

Microwave efficiency trends of the crude oils was initially predicted based on the stability of asphaltenes for all crude oil blends. Crude oil C1 had unstable asphaltenes by definition of CII, along with the highest weight percent of asphaltenes and resins. The dielectric constant decreased with the addition of precipitant solvents due to mainly a precipitation effect where separating out the most polar fraction out of mixture reduced the relative polarity. Meanwhile, C2 and C3 produced the opposite trend for the dielectric constant, where both oil samples had more stable asphaltenes. For these two oil samples, resins are freed as a result of asphaltene precipitation, increasing the relative polarity of the blends. Dispersant mixtures, on the other hand, did not experience change to the relative polarity of the oil mixtures due to keeping the composition of the crude oil constant. Balancing the composition change of crude oil samples when precipitating asphaltenes can lead to maximizing the dielectric constant.

The type of asphaltene solvent (precipitant, dispersant) used can lead to large changes to crude oil properties, and consequently microwave efficiency. Experimental results showed that crude oils tested with unstable asphaltenes and a high asphaltenes and resins content produced the greatest absorption when using precipitant mixtures (435%). In contrast, bulk crude oils tested with stable asphaltenes and low asphaltenes and resins content produced the highest absorption increases (171%, 420%) when mixed with dispersants. It is recommended that in the field scale, such solvents are not used due to possible toxicity of the chemicals as well as the preceding negative environmental footprint. Commercially viable asphaltene precipitants and dispersants should be used instead to test the possible absorption percentage increases.

When temperature dependence tests were conducted, it was found that heavy oils' dielectric constant will increase when exposed to temperature increases regardless of crude oil composition. Similarly, loss tangent of bulk samples have shown an increase with increase of temperature values. Results of such tests revealed that the performance of dielectric properties are significantly tied to temperature increase.

Significance of these results merit that the fundamental dielectric properties of the oil phase will change significantly when exposed to elevated temperatures. Since the objective of electromagnetic heating is to increase the temperature of the heavy oil in place to increase flow, reservoir scale temperature increases can be expected to be much higher than the experimentally produced temperature results. With that in mind, it is expected that the oil phase will experience much more drastic changes to its dielectric properties under such thermally dynamic environments.

From the percentage difference results of the dielectric constant and loss tangent, a new correlation method can be introduced in examining the microwave potential of heavy oil, as seen in table 3.3. The narrow use of colloidal instability index as a benchmark to predict microwave behavior only served to project an increase or decrease of the dielectric properties, not quantifying such changes. Physical properties of the crude oil should be used along with SARA properties to determine microwave efficiency. Thus, when aiming for the greatest loss tangent percentage difference, desired properties include low API (6.11), high viscosity (1.00E+07), high asphaltenes and resins content (40.08%, 20.14%), low saturates and aromatics content (10.68%, 29.1%), and a high colloidal instability index (1.0309). When the objective is to increase energy storage in terms of dielectric constant percentage difference (2.26%), high API gravity (17.12), low viscosity (496), low polar fractions (10.68%, 29.1%) and CII values (0.7422) are warranted.

Microwaved percentages warranted similar trends, but with lower performance results. New microwave parameters should be adjusted, such as heating time and frequency input should be reconsidered to achieve the optimal loss tangent and dielectric constant increase.

A new perspective of viewing microwave candidacy is introduced with the focus on SARA fractionation behavior. For the first time the effects of microwave efficiency of heavy oil was investigated in conjunction with its SARA fractionations.

REFERENCES

Abernethy, E. R. (1976, July 1). Production Increase of Heavy Oils by Electromagnetic Heating. Petroleum Society of Canada. doi: 10.2118/76-03-12

Acosta, E. 2010. "Achieving sustainable, optimal SAGD operations." Journal of Petroleum Technology, Vol. 62(11), 24-28.

Alshaikh, M., Huff, G., Hascakir, B., An Innovative Dielectric Constant Measurement Method to Determine the Ideal Surfactant Candidate to Enhance Heavy Oil Recovery, SPE Canada Heavy Oil Technical Conference, 13-14 March 2018, Calgary, Alberta, Canada. SPE-189752-MS.

Ashoori, S., Sharifi, M., Masoumi, M., & Salehi, M. M. (2017). The relationship between SARA fractions and crude oil stability. Egyptian Journal of Petroleum, 26(1), 209-213.

Asomaning, S. 2003. Test Methods for Determining Asphaltenes Stability in Crude Oils. Petroleum Science and Technology 21 (3-4): 581-590.

ASTM D2007-11(2016) Standard Test Method for Clay-gel Adsorption Chromatographic Method for Hydrocarbon Group Analysis, ASTM International, West Conshohocken, PA, 2016, https://doi.org/10.1520/D2007-11R16

ASTM D287-12b Standard Test Method for API Gravity of Crude Petroleum and Petroleum Products (Hydrometer Method), ASTM International, West Conshohocken, PA, 2012, https://doi.org/10.1520/D0287-12B

ASTM D3279-12e1 (2012) Method ASTM D 3279: Standard Test Method for Normal Heptane Insolubles., ASTM International, West Conshohocken, PA, 2012, https://doi.org/10.1520/D3279-12E01

ASTM D445-17 Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity), ASTM International, West Conshohocken, PA, 2017, https://doi.org/10.1520/D0445-17

Beal, C. (1946, December 1). The Viscosity of Air, Water, Natural Gas, Crude Oil and Its Associated Gases at Oil Field Temperatures and Pressures. Society of Petroleum Engineers. doi:10.2118/946094-G

Bird, R. B., Stewart, W. E., & Lightfoot, E. N. (1960). Transport Phenomena John Wiley & Sons. New York, 413.

Chakma, A., & Jha, K. N. (1992, January 1). Heavy-Oil Recovery from Thin Pay Zones by Electromagnetic Heating. Society of Petroleum Engineers. doi:10.2118/24817-MS

Chhetri, A.B. and Islam, M.R. 2008. A Critical Review of Electromagnetic Heating for Enhanced Oil Recovery, Petroleum Science and Technology. Journal of Petroleum Technology 26 (14): 1619—1631. doi: 10.1080/10916460701287607

Deo, M. D., Hwang, J., & Hanson, F. V. (1993). The effect of cosolubilizing lighter components on the asphaltene content of heavy oils. Fuel Processing Technology, 34(3), 217-228.

Fernández, Y., Arenillas, A., & Menéndez, J. Á. (2011). Microwave heating applied to pyrolysis. In Advances in induction and microwave heating of mineral and organic materials. InTech.

Fröhlich, H. (1949). Theory of dielectrics: dielectric constant and dielectric loss. Oxford: Clarendon Press.

Godio, A. (2007). Open ended-coaxial cable measurements of saturated sandy soils. American Journal of Environmental Sciences, 3(3), 175-182.

Hamon, B. (1952). An approximate method for deducing dielectric loss factor from direct-current measurements. Proceedings of the IEE - Part IV: Institution Monographs, 99(3), 151-155. doi:10.1049/pi-4.1952.0016

Harris, F. E., & Alder, B. J. (1953). Dielectric polarization in polar substances. The Journal of Chemical Physics, 21(6), 1031-1038.

Harris, F. E., & O'Konski, C. T. (1957). Dielectric properties of aqueous ionic solutions at microwave frequencies. The Journal of Physical Chemistry, 61(3), 310-319.

Hascakir, B., Acar, C., Akin, S., Microwave Assisted Heavy Oil Production: An Experimental Approach, Energy and Fuels, 23(12), 6033-6039, 2009. doi: 10.1021/ef9007517

Hascakir, B., Akin, S., Recovery of Turkish Oil Shales by Electromagnetic Heating and Determination of the Dielectric Properties of Oil Shales by an Analytical Method, Energy and Fuels, 24(1), 503-509, 2010, doi: 10.1021/ef900868w

Hennelly, E. J., Heston Jr, W. M., & Smyth, C. P. (1948). Microwave Absorption and Molecular Structure in Liquids. III. Dielectric Relaxation and Structure in Organic Halides1. Journal of the American Chemical Society, 70(12), 4102-4111.

Hibi, R., Tagami, K., Kobayashi, K., Liang, Y., Honda, H., Murata, S., ... & Boek, E. S. (2014, December). Investigation of asphaltene-asphaltene association and aggregation for compositional reservoir simulators by quantitative molecular representations. In International Petroleum Technology Conference. International Petroleum Technology Conference.

Huang, Y. F., Chiueh, P. T., & Lo, S. L. (2016). A review on microwave pyrolysis of lignocellulosic biomass. Sustainable Environment Research, 26(3), 103-109.

Huang, S., Huang, C., Cheng, L., Liu, T., Chen, Z., & Mao, W. (2015, November 18). Experiment Investigation of Steam Flooding of Horizontal Wells for Thin and Heterogeneous Heavy Oil Reservoirs. Society of Petroleum Engineers. doi:10.2118/177030-MS

Jones, D. A., Lelyveld, T. P., Mavrofidis, S. D., Kingman, S. W., & Miles, N. J. (2002). Microwave heating applications in environmental engineering—a review. Resources, conservation and recycling, 34(2), 75-90.

Kar, T., Hascakir, B., The Role of Resins, Asphaltenes, and Water in Water-Oil Emulsion Breaking with Microwave Heating, Energy and Fuels, 2015, 29, 3684-3690, doi: 10.1021/acs.energyfuels.5b00662

Kasevich, R. S., Price, S. L., Faust, D. L., & Fontaine, M. F. (1994, January). Pilot testing of a radio frequency heating system for enhanced oil recovery from diatomaceous earth. In SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers.

Kejing et al., Fuel 103 (2013): 843-849. Al-Rujaibi, O., et al. Journal of Petroleum Science and Engineering 144 (2016): 66-75. Guo et al. Fuel 185 (2016): 886-902.

Kontorovich, A. (2009). Estimate of global oil resource and the forecast for global oil production in the 21st century. Russian Geology and Geophysics, 50(4), 237-242. doi:10.1016/j.rgg.2009.03.001

Kovscek, A. R. (2012). Emerging challenges and potential futures for thermally enhanced oil recovery. Journal of Petroleum Science and Engineering, 98, 130-143.

Krupka, J., Geyer, R. G., Kuhn, M., & Hinken, J. H. (1994). Dielectric properties of single crystals of Al/sub 2/O/sub 3/, LaAlO/sub 3/, NdGaO/sub 3/, SrTiO/sub 3/, and MgO at cryogenic temperatures. IEEE Transactions on Microwave Theory and Techniques, 42(10), 1886-1890.

Leontaritis, K. J., Amaefule, J. O., & Charles, R. E. (1994). A systematic approach for the prevention and treatment of formation damage caused by asphaltene deposition. SPE Production & Facilities, 9(03), 157-164.

Liao, H., Morte, M., Bloom, E., Huff, G., & Hascakir, B. (2018, April 22). Controlling Microwave Penetration and Absorption in Heavy Oil Reservoirs. Society of Petroleum Engineers. doi:10.2118/190089-MS

Liao, H., Morte, M., & Hascakir, B. (2019, April 26). Effect of Crude Oil Composition on Microwave Absorption of Heavy Oils. Society of Petroleum Engineers.

Lowry, H.H. 1929. The Significance of the Dielectric Constant of a Mixture. *Journal of Franklin Institute* **203** (03): 433-439.

Marques, L. C., Pereira, J. O., Bueno, A. D., Marques, V. S., Lucas, E. F., Mansur, C. R., ... & González, G. (2012). A study of asphaltene-resin interactions. Journal of the Brazilian Chemical Society, 23(10), 1880-1888.

Martinez, A., & Byrnes, A. P. (2001). Modeling dielectric-constant values of geologic materials: An aid to ground-penetrating radar data collection and interpretation. Lawrence, Kansas: Kansas Geological Survey.

Meyer, R. F., & Attanasi, E. (2003). Natural Bitumen and Extra-Heavy Oil. *2003 Survey of Energy Resources,* 93-117. doi:10.1016/b978-008044410-9/50008-5

Mitchell, D. L., Speight, J. G. 1973. The Solubility of Asphaltenes in Hydrocarbon Solvents. Fuel 52(02): 149-152. https://doi.org/10.1016/0016-2361(73)90040-9

Morte, M., Huff, G., Hascakir, B., Factors Affecting Electromagnetic Wave Penetration in Heavy Oil Reservoirs, SPE Canada Heavy Oil Technical Conference, 13-14 March 2018, Calgary, Alberta, Canada. SPE-189746-MS.

Mukhametshina, A., Martynova, E., Electromagnetic Heating of Heavy Oil and Bitumen: A review of Experimental Studies and Field Applications, Journal of Petroleum Engineering, Volume 2013 (2013), Article ID 476519.

Mullin J. (1995) Microwave processing. In: Gould G.W. (eds) New Methods of Food Preservation. Springer, Boston, MA

Mullins, Oliver C., et al. “The Colloidal Structure of Crude Oil and the Structure of Oil Reservoirs.” Energy & Fuels, vol. 21, no. 5, 2007, pp. 2785–2794., doi: 10.1021/ef0700883.

Mutyala, S., Fairbridge, C., Paré, J. J., Bélanger, J. M., Ng, S., & Hawkins, R. (2010). Microwave applications to oil sands and petroleum: A review. Fuel Processing Technology, 91(2), 127-135. doi:10.1016/j.fuproc.2009.09.009

Nalwaya, V., Tantayakom, V., Piumsomboon, P., & Fogler, S. (1999). Studies on asphaltenes through analysis of polar fractions. Industrial & engineering chemistry research, 38(3), 964-972.

Onsager, L. (1936). Electric moments of molecules in liquids. Journal of the American Chemical Society, 58(8), 1486-1493.

Osepchuk, J. (1984). A History of Microwave Heating Applications. IEEE Transactions on Microwave Theory and Techniques, 32(9), 1200-1224. doi:10.1109/tmtt.1984.1132831

Ovalles, C., Fonseca, A., Lara, A., Alvarado, V., Urrecheaga, K., Ranson, A., & Mendoza, H. (2002, January 1). Opportunities of Downhole Dielectric Heating in Venezuela: Three Case Studies Involving Medium, Heavy and Extra-Heavy Crude Oil Reservoirs. Society of Petroleum Engineers. doi:10.2118/78980-MS

Pauling, L. (1932). The nature of the chemical bond. IV. The energy of single bonds and the relative electronegativity of atoms. Journal of the American Chemical Society, 54(9), 3570-3582.

Prakoso, A. A., Punase, A. D., & Hascakir, B. (2017, February 1). A Mechanistic Understanding of Asphaltenes Precipitation from Varying-Saturate-Concentration Perspectives. Society of Petroleum Engineers. doi:10.2118/177280-PA

Prats, M., & Prats, M. (1982). *Thermal recovery* (pp. 6-14). Richardson, TX: Henry L. Doherty Memorial Fund of AIME, Society of Petroleum Engineers.

Punase, A., Hascakir, B., Stability Determination of Asphaltenes through Dielectric Constant Measurements of Polar Oil Fractions, Energy and Fuels, 2017, 31 (1), 65-77.

Punase, A., Prakoso, A.A., Hascakir, B., The Polarity of Crude Oil Fractions Affects the Asphaltenes Stability, SPE Western Regional Meeting, 23-26 May 2016, Anchorage, Alaska, USA, SPE-180423-MS.

Roberts, J. E., & Cook, H. F. (1952). Microwaves in medical and biological research. British Journal of Applied Physics, 3(2), 33.

Sahni, A., Kumar, M., & Knapp, R. B. (2000, January 1). Electromagnetic Heating Methods for Heavy Oil Reservoirs. Society of Petroleum Engineers. doi:10.2118/62550-MS

Shkalikov, N. V, Vasil'ev, S. G., Skirda, V. K. 2010. "Peculiarities of Asphaltene Precipitation in n-Alkane–Oil Systems." Colloid Journal, Vol. 72, No. 1, pp. 133–140.

Shen, L. C., Savre, W. C., Price, J. M., & Athavale, K. (1985). Dielectric properties of reservoir rocks at ultra-high frequencies. Geophysics, 50(4), 692-704, doi: 10.1016/0148-9062(86)90412-2.

Speight, J. G. 1991. The Chemistry and Technology of Petroleum. 2nd ed.; Marcel Dekker, Inc. ISBN 0-8247-8481-2.

Speight, J. G. (2004). Petroleum Asphaltenes-Part 1: Asphaltenes, resins and the structure of petroleum. Oil & gas science and technology, 59(5), 467-477.

Sresty, G. C., Dev, H., Snow, R. H., & Bridges, J. E. (1986). Recovery of bitumen from tar sand deposits with the radio frequency process. SPE Reservoir Engineering, 1(01), 85-94.

Thostenson, E. T., & Chou, T. W. (1999). Microwave processing: fundamentals and applications. Composites Part A: Applied Science and Manufacturing, 30(9), 1055-1071.

Von Hippel, A. R. (1954). Dielectric materials and applications (Vol. 2). Artech House on Demand.

Wang, W. C. (1986). Electromagnetic wave theory (pp. 36-42). Wiley, New York.

Weir, W. (1974). Automatic measurement of complex dielectric constant and permeability at microwave frequencies. Proceedings of the IEEE, 62(1), 33-36. doi:10.1109/proc.1974.9382

Wyman Jr, J. (1936). Polarization and dielectric constant of liquids. Journal of the American Chemical Society, 58(8), 1482-1486. doi:10.1021/ja01299a049

Zhu, J., Kuznetsov, A.V., and Sandeep, K.P. 2007. Mathematical Modeling of Continuous Flow Microwave Heating of Liquids. International Journal of Thermal Sciences 46 (4): 328—341. https://doi.org/10.1016/j.ijthermalsci.2006.06.005.

APPENDIX:

Table A-1: Dielectric properties for crude oil C1 blends with nC5

	nC5											
	10%				20%				50%			
frequency(Hz)	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp
2.82E+08	2.56	0.07	0.03	0.44	2.73	0.05	0.02	0.69	2.55	-0.08	-0.03	0.37
3.22E+08	2.40	0.03	0.01	0.93	2.60	0.05	0.02	0.63	2.52	-0.05	-0.02	0.58
4.02E+08	2.46	0.02	0.01	1.64	2.62	0.05	0.02	0.61	2.53	-0.08	-0.03	0.39
4.42E+08	2.54	0.04	0.01	0.84	2.70	0.06	0.02	0.55	2.55	-0.02	-0.01	1.46
5.22E+08	2.51	0.03	0.01	1.04	2.67	0.06	0.02	0.54	2.54	0.04	0.02	0.69
5.62E+08	2.54	0.03	0.01	1.16	2.64	0.05	0.02	0.58	2.53	-0.05	-0.02	0.65
6.42E+08	2.59	0.02	0.01	1.52	2.64	0.05	0.02	0.61	2.56	-0.03	-0.01	0.96
6.82E+08	2.50	0.03	0.01	0.96	2.64	0.06	0.02	0.51	2.52	-0.01	0.00	4.29
7.62E+08	2.47	0.03	0.01	1.06	2.65	0.06	0.02	0.55	2.51	0.03	0.01	1.11
8.02E+08	2.59	0.04	0.01	0.83	2.64	0.05	0.02	0.61	2.54	-0.03	-0.01	1.08
8.82E+08	2.58	0.02	0.01	1.31	2.65	0.05	0.02	0.61	2.54	-0.01	0.00	3.14
9.22E+08	2.51	0.03	0.01	1.22	2.62	0.06	0.02	0.54	2.53	0.01	0.00	4.24
1E+09	2.53	0.02	0.01	1.45	2.63	0.06	0.02	0.53	2.52	0.02	0.01	1.99
1.04E+09	2.57	0.01	0.01	2.17	2.65	0.06	0.02	0.56	2.53	0.02	0.01	1.38
1.12E+09	2.56	0.03	0.01	1.24	2.66	0.06	0.02	0.55	2.52	0.02	0.01	1.75
1.16E+09	2.57	0.01	0.00	2.65	2.62	0.06	0.02	0.56	2.54	-0.01	0.00	3.69
1.24E+09	2.59	0.02	0.01	1.89	2.63	0.05	0.02	0.58	2.54	0.00	0.00	8.11
1.28E+09	2.53	0.03	0.01	1.10	2.65	0.06	0.02	0.53	2.52	0.05	0.02	0.63
1.36E+09	2.53	0.02	0.01	1.50	2.66	0.06	0.02	0.53	2.52	0.03	0.01	1.08
1.4E+09	2.60	0.02	0.01	1.83	2.66	0.06	0.02	0.57	2.55	0.02	0.01	1.48
1.48E+09	2.61	0.02	0.01	1.65	2.67	0.06	0.02	0.55	2.55	0.02	0.01	1.49
1.52E+09	2.55	0.01	0.01	2.24	2.64	0.06	0.02	0.52	2.53	0.04	0.02	0.70
1.6E+09	2.55	0.03	0.01	0.93	2.63	0.06	0.02	0.51	2.54	0.07	0.03	0.46
1.64E+09	2.61	0.01	0.00	2.99	2.65	0.06	0.02	0.55	2.53	0.03	0.01	0.95
1.72E+09	2.57	0.01	0.00	2.45	2.65	0.06	0.02	0.55	2.53	0.06	0.03	0.48
1.76E+09	2.60	0.02	0.01	1.36	2.64	0.06	0.02	0.53	2.55	0.02	0.01	1.72
1.84E+09	2.62	0.03	0.01	1.14	2.63	0.06	0.02	0.54	2.55	0.03	0.01	1.03
1.88E+09	2.56	0.04	0.01	0.85	2.67	0.06	0.02	0.51	2.54	0.08	0.03	0.39
1.96E+09	2.56	0.01	0.00	2.74	2.65	0.06	0.02	0.52	2.55	0.08	0.03	0.39
2E+09	2.63	0.02	0.01	1.58	2.66	0.06	0.02	0.55	2.58	0.06	0.02	0.55
2.08E+09	2.65	0.03	0.01	1.06	2.67	0.06	0.02	0.55	2.57	0.09	0.03	0.35

2.12E+09	2.59	0.03	0.01	1.19	2.67	0.06	0.02	0.52	2.56	0.09	0.04	0.33
2.2E+09	2.62	0.03	0.01	1.12	2.68	0.06	0.02	0.53	2.57	0.10	0.04	0.31
2.24E+09	2.66	0.03	0.01	0.95	2.70	0.06	0.02	0.54	2.57	0.12	0.05	0.26
2.32E+09	2.64	0.05	0.02	0.66	2.71	0.06	0.02	0.53	2.57	0.12	0.05	0.25
2.36E+09	2.65	0.05	0.02	0.66	2.68	0.06	0.02	0.51	2.58	0.11	0.04	0.27
2.44E+09	2.66	0.06	0.02	0.55	2.63	0.06	0.03	0.43	2.58	0.13	0.05	0.25
2.48E+09	2.62	0.06	0.02	0.50	2.68	0.07	0.02	0.48	2.57	0.15	0.06	0.21
2.56E+09	2.62	0.06	0.02	0.50	2.70	0.07	0.02	0.49	2.55	0.15	0.06	0.20
2.6E+09	2.68	0.07	0.02	0.48	2.69	0.06	0.02	0.50	2.58	0.13	0.05	0.24
2.68E+09	2.70	0.07	0.03	0.46	2.70	0.06	0.02	0.50	2.59	0.18	0.07	0.18
2.72E+09	2.64	0.09	0.03	0.37	2.70	0.07	0.03	0.46	2.57	0.21	0.08	0.15
2.8E+09	2.64	0.08	0.03	0.37	2.70	0.07	0.03	0.46	2.58	0.19	0.07	0.17
2.84E+09	2.69	0.08	0.03	0.40	2.71	0.07	0.02	0.49	2.59	0.20	0.08	0.16
2.92E+09	2.68	0.08	0.03	0.40	2.71	0.07	0.02	0.48	2.59	0.21	0.08	0.15
2.96E+09	2.65	0.08	0.03	0.40	2.70	0.07	0.03	0.47	2.58	0.19	0.08	0.16
3.04E+09	2.67	0.09	0.03	0.36	2.71	0.07	0.03	0.47	2.59	0.20	0.08	0.16
3.08E+09	2.66	0.09	0.03	0.36	2.72	0.07	0.03	0.47	2.58	0.23	0.09	0.14
3.16E+09	2.66	0.10	0.04	0.32	2.72	0.07	0.03	0.46	2.58	0.24	0.09	0.13
3.2E+09	2.71	0.09	0.03	0.35	2.72	0.07	0.02	0.47	2.59	0.24	0.09	0.13
3.28E+09	2.73	0.11	0.04	0.30	2.74	0.07	0.02	0.47	2.60	0.25	0.09	0.13
3.32E+09	2.65	0.11	0.04	0.29	2.73	0.07	0.03	0.44	2.58	0.27	0.10	0.12
3.4E+09	2.65	0.11	0.04	0.30	2.73	0.07	0.03	0.44	2.59	0.27	0.10	0.12
3.44E+09	2.74	0.13	0.05	0.26	2.75	0.07	0.03	0.45	2.60	0.28	0.11	0.11
3.52E+09	2.73	0.12	0.05	0.26	2.75	0.07	0.03	0.45	2.61	0.27	0.11	0.11
3.56E+09	2.68	0.14	0.05	0.23	2.72	0.07	0.03	0.43	2.59	0.29	0.11	0.11
3.64E+09	2.69	0.14	0.05	0.23	2.73	0.07	0.03	0.43	2.59	0.28	0.11	0.11
3.68E+09	2.68	0.14	0.05	0.22	2.73	0.08	0.03	0.43	2.59	0.32	0.12	0.10
3.76E+09	2.67	0.13	0.05	0.25	2.75	0.07	0.03	0.44	2.59	0.34	0.13	0.09
3.8E+09	2.74	0.14	0.05	0.24	2.75	0.07	0.03	0.44	2.61	0.32	0.12	0.10
3.88E+09	2.75	0.15	0.05	0.22	2.76	0.08	0.03	0.43	2.61	0.34	0.13	0.09
3.96E+09	2.75	0.15	0.06	0.21	2.76	0.08	0.03	0.43	2.62	0.36	0.14	0.09
4E+09	2.68	0.16	0.06	0.20	2.76	0.08	0.03	0.42	2.58	0.36	0.14	0.09

Table A-2: Dielectric properties for crude oil C1 blends with nC7

	nC7											
	10%				20%				50%			
frequency(Hz)	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp
2.82E+08	2.81	0.09	0.03	0.37	2.66	0.12	0.05	0.26	2.57	0.16	0.06	0.20
3.22E+08	2.75	0.04	0.01	0.80	2.61	0.12	0.05	0.26	2.51	0.16	0.06	0.19
4.02E+08	2.72	0.01	0.00	4.15	2.62	0.12	0.05	0.26	2.55	0.15	0.06	0.20
4.42E+08	2.73	0.03	0.01	1.15	2.64	0.12	0.05	0.26	2.52	0.17	0.07	0.19
5.22E+08	2.68	0.00	0.00	6.72	2.62	0.12	0.05	0.26	2.54	0.17	0.07	0.19
5.62E+08	2.69	-0.06	-0.02	0.55	2.62	0.12	0.04	0.27	2.56	0.16	0.06	0.20
6.42E+08	2.70	-0.01	0.00	3.29	2.65	0.12	0.04	0.27	2.57	0.16	0.06	0.20
6.82E+08	2.71	0.08	0.03	0.42	2.61	0.12	0.05	0.26	2.51	0.17	0.07	0.18
7.62E+08	2.71	0.11	0.04	0.29	2.63	0.12	0.05	0.26	2.51	0.17	0.07	0.18
8.02E+08	2.75	0.07	0.03	0.46	2.65	0.12	0.04	0.27	2.58	0.16	0.06	0.20
8.82E+08	2.74	0.06	0.02	0.51	2.64	0.12	0.05	0.27	2.59	0.16	0.06	0.19
9.22E+08	2.71	0.05	0.02	0.65	2.64	0.12	0.04	0.27	2.55	0.16	0.06	0.19
1E+09	2.69	0.01	0.00	2.84	2.63	0.12	0.05	0.26	2.55	0.16	0.06	0.19
1.04E+09	2.69	0.02	0.01	2.11	2.63	0.12	0.05	0.26	2.55	0.16	0.06	0.19
1.12E+09	2.69	0.03	0.01	0.91	2.63	0.12	0.05	0.26	2.53	0.17	0.07	0.19
1.16E+09	2.70	0.03	0.01	1.27	2.64	0.12	0.05	0.27	2.56	0.16	0.06	0.19
1.24E+09	2.73	0.05	0.02	0.64	2.65	0.12	0.05	0.26	2.57	0.16	0.06	0.19
1.28E+09	2.71	0.09	0.03	0.37	2.63	0.12	0.05	0.27	2.52	0.17	0.07	0.18
1.36E+09	2.70	0.09	0.03	0.36	2.62	0.12	0.05	0.26	2.51	0.17	0.07	0.19
1.4E+09	2.75	0.05	0.02	0.65	2.66	0.12	0.04	0.27	2.58	0.16	0.06	0.19
1.48E+09	2.73	0.04	0.01	0.85	2.66	0.12	0.05	0.26	2.59	0.16	0.06	0.19
1.52E+09	2.72	0.04	0.02	0.74	2.64	0.12	0.05	0.26	2.54	0.16	0.06	0.19
1.6E+09	2.71	0.07	0.03	0.46	2.66	0.12	0.05	0.26	2.56	0.16	0.06	0.19
1.64E+09	2.70	0.06	0.02	0.50	2.67	0.12	0.05	0.26	2.55	0.17	0.07	0.19
1.72E+09	2.71	0.05	0.02	0.71	2.64	0.12	0.05	0.26	2.55	0.17	0.07	0.18
1.76E+09	2.74	0.05	0.02	0.60	2.65	0.12	0.05	0.26	2.57	0.16	0.06	0.19
1.84E+09	2.75	0.06	0.02	0.53	2.66	0.12	0.04	0.27	2.59	0.16	0.06	0.19
1.88E+09	2.75	0.08	0.03	0.40	2.65	0.12	0.05	0.26	2.53	0.17	0.07	0.19
1.96E+09	2.74	0.06	0.02	0.52	2.64	0.12	0.05	0.26	2.56	0.17	0.06	0.19
2E+09	2.77	0.05	0.02	0.63	2.67	0.12	0.04	0.27	2.61	0.16	0.06	0.19
2.08E+09	2.77	0.05	0.02	0.63	2.68	0.12	0.05	0.26	2.61	0.16	0.06	0.19
2.12E+09	2.74	0.06	0.02	0.57	2.67	0.12	0.05	0.26	2.57	0.17	0.06	0.19
2.2E+09	2.75	0.05	0.02	0.65	2.67	0.12	0.05	0.26	2.58	0.17	0.06	0.19

2.24E+09	2.76	0.07	0.03	0.45	2.67	0.12	0.05	0.26	2.59	0.17	0.06	0.19
2.32E+09	2.77	0.08	0.03	0.41	2.67	0.12	0.05	0.26	2.60	0.17	0.07	0.19
2.36E+09	2.78	0.09	0.03	0.37	2.68	0.12	0.05	0.26	2.62	0.17	0.06	0.19
2.44E+09	2.74	0.09	0.03	0.34	2.66	0.12	0.05	0.26	2.62	0.17	0.06	0.19
2.48E+09	2.78	0.12	0.04	0.26	2.67	0.12	0.05	0.26	2.59	0.17	0.07	0.18
2.56E+09	2.78	0.13	0.05	0.25	2.68	0.12	0.05	0.26	2.61	0.17	0.07	0.19
2.6E+09	2.79	0.12	0.04	0.28	2.71	0.12	0.04	0.27	2.65	0.17	0.06	0.19
2.68E+09	2.78	0.12	0.04	0.27	2.71	0.12	0.05	0.26	2.65	0.17	0.06	0.19
2.72E+09	2.76	0.12	0.04	0.28	2.70	0.12	0.05	0.26	2.61	0.17	0.07	0.18
2.8E+09	2.78	0.11	0.04	0.29	2.71	0.12	0.05	0.26	2.61	0.17	0.07	0.19
2.84E+09	2.79	0.13	0.05	0.25	2.72	0.13	0.05	0.26	2.65	0.17	0.07	0.18
2.92E+09	2.80	0.16	0.06	0.21	2.72	0.13	0.05	0.25	2.63	0.18	0.07	0.18
2.96E+09	2.81	0.15	0.05	0.22	2.71	0.12	0.05	0.26	2.63	0.17	0.06	0.19
3.04E+09	2.81	0.16	0.06	0.20	2.73	0.13	0.05	0.26	2.64	0.17	0.06	0.19
3.08E+09	2.80	0.18	0.07	0.18	2.72	0.13	0.05	0.25	2.62	0.18	0.07	0.18
3.16E+09	2.79	0.18	0.07	0.18	2.71	0.13	0.05	0.25	2.62	0.18	0.07	0.18
3.2E+09	2.81	0.16	0.06	0.20	2.74	0.13	0.05	0.25	2.66	0.17	0.07	0.18
3.28E+09	2.81	0.14	0.05	0.23	2.75	0.13	0.05	0.25	2.68	0.18	0.07	0.18
3.32E+09	2.80	0.17	0.06	0.19	2.73	0.13	0.05	0.25	2.62	0.18	0.07	0.18
3.4E+09	2.79	0.17	0.06	0.19	2.74	0.13	0.05	0.25	2.63	0.18	0.07	0.18
3.44E+09	2.82	0.18	0.07	0.18	2.74	0.13	0.05	0.24	2.67	0.18	0.07	0.18
3.52E+09	2.82	0.24	0.08	0.14	2.74	0.13	0.05	0.24	2.66	0.18	0.07	0.17
3.56E+09	2.81	0.19	0.07	0.17	2.74	0.13	0.05	0.25	2.64	0.18	0.07	0.18
3.64E+09	2.82	0.22	0.08	0.15	2.75	0.13	0.05	0.25	2.65	0.18	0.07	0.18
3.68E+09	2.82	0.24	0.09	0.14	2.73	0.13	0.05	0.24	2.64	0.18	0.07	0.17
3.76E+09	2.79	0.25	0.09	0.13	2.74	0.14	0.05	0.24	2.64	0.18	0.07	0.17
3.8E+09	2.84	0.22	0.08	0.15	2.75	0.13	0.05	0.24	2.68	0.18	0.07	0.18
3.88E+09	2.84	0.23	0.08	0.14	2.75	0.14	0.05	0.24	2.69	0.18	0.07	0.18
3.96E+09	2.83	0.26	0.09	0.13	2.77	0.14	0.05	0.23	2.69	0.18	0.07	0.17
4E+09	2.81	0.27	0.09	0.12	2.74	0.14	0.05	0.23	2.64	0.18	0.07	0.17

Table A-3: Dielectric properties for crude oil C1 blends with toluene

	Toluene											
	10%				20%				50%			
frequency(Hz)	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp
2.82E+08	2.76	0.05	0.02	0.60	2.86	0.05	0.02	0.71	2.92	0.04	0.01	0.81
3.22E+08	2.72	0.06	0.02	0.55	2.74	0.05	0.02	0.60	2.75	0.05	0.02	0.61
4.02E+08	2.73	0.06	0.02	0.58	2.76	0.05	0.02	0.62	2.76	0.05	0.02	0.61
4.42E+08	2.75	0.06	0.02	0.56	2.79	0.06	0.02	0.57	2.80	0.06	0.02	0.57
5.22E+08	2.74	0.06	0.02	0.54	2.79	0.06	0.02	0.54	2.81	0.06	0.02	0.53
5.62E+08	2.73	0.06	0.02	0.56	2.75	0.05	0.02	0.62	2.75	0.05	0.02	0.67
6.42E+08	2.73	0.06	0.02	0.57	2.75	0.05	0.02	0.63	2.75	0.05	0.02	0.66
6.82E+08	2.74	0.06	0.02	0.57	2.76	0.06	0.02	0.55	2.76	0.06	0.02	0.53
7.62E+08	2.72	0.06	0.02	0.54	2.74	0.06	0.02	0.50	2.75	0.06	0.02	0.50
8.02E+08	2.72	0.06	0.02	0.57	2.77	0.05	0.02	0.63	2.77	0.05	0.02	0.67
8.82E+08	2.74	0.06	0.02	0.56	2.79	0.05	0.02	0.60	2.79	0.05	0.02	0.61
9.22E+08	2.74	0.06	0.02	0.52	2.77	0.06	0.02	0.51	2.75	0.06	0.02	0.52
1E+09	2.73	0.06	0.02	0.52	2.75	0.06	0.02	0.52	2.75	0.06	0.02	0.51
1.04E+09	2.75	0.06	0.02	0.52	2.77	0.06	0.02	0.54	2.78	0.06	0.02	0.54
1.12E+09	2.74	0.06	0.02	0.53	2.77	0.06	0.02	0.54	2.78	0.06	0.02	0.54
1.16E+09	2.74	0.06	0.02	0.53	2.75	0.06	0.02	0.56	2.74	0.06	0.02	0.56
1.24E+09	2.74	0.06	0.02	0.53	2.75	0.06	0.02	0.57	2.74	0.06	0.02	0.57
1.28E+09	2.74	0.06	0.02	0.51	2.77	0.06	0.02	0.52	2.77	0.06	0.02	0.51
1.36E+09	2.75	0.06	0.02	0.50	2.77	0.06	0.02	0.51	2.76	0.07	0.02	0.49
1.4E+09	2.74	0.06	0.02	0.54	2.77	0.06	0.02	0.56	2.78	0.06	0.02	0.58
1.48E+09	2.75	0.06	0.02	0.53	2.76	0.06	0.02	0.54	2.77	0.06	0.02	0.56
1.52E+09	2.75	0.06	0.02	0.51	2.77	0.06	0.02	0.50	2.76	0.07	0.02	0.49
1.6E+09	2.76	0.06	0.02	0.52	2.76	0.06	0.02	0.51	2.77	0.06	0.02	0.51
1.64E+09	2.75	0.06	0.02	0.51	2.77	0.06	0.02	0.56	2.77	0.06	0.02	0.56
1.72E+09	2.77	0.06	0.02	0.54	2.80	0.06	0.02	0.56	2.79	0.06	0.02	0.54
1.76E+09	2.76	0.06	0.02	0.52	2.76	0.06	0.02	0.53	2.76	0.06	0.02	0.51
1.84E+09	2.75	0.06	0.02	0.54	2.76	0.06	0.02	0.55	2.75	0.06	0.02	0.55
1.88E+09	2.78	0.06	0.02	0.52	2.80	0.06	0.02	0.52	2.78	0.06	0.02	0.52
1.96E+09	2.76	0.06	0.02	0.53	2.79	0.06	0.02	0.52	2.79	0.06	0.02	0.51
2E+09	2.78	0.06	0.02	0.54	2.80	0.06	0.02	0.56	2.79	0.06	0.02	0.56
2.08E+09	2.79	0.06	0.02	0.54	2.81	0.06	0.02	0.56	2.80	0.06	0.02	0.55
2.12E+09	2.79	0.06	0.02	0.51	2.80	0.06	0.02	0.51	2.80	0.07	0.02	0.49
2.2E+09	2.79	0.06	0.02	0.51	2.80	0.06	0.02	0.51	2.79	0.07	0.02	0.49

2.24E+09	2.81	0.06	0.02	0.51	2.83	0.06	0.02	0.54	2.81	0.06	0.02	0.54
2.32E+09	2.81	0.06	0.02	0.50	2.84	0.06	0.02	0.53	2.83	0.06	0.02	0.51
2.36E+09	2.80	0.06	0.02	0.50	2.81	0.06	0.02	0.52	2.79	0.07	0.02	0.50
2.44E+09	2.79	0.06	0.02	0.50	2.79	0.07	0.02	0.50	2.79	0.06	0.02	0.50
2.48E+09	2.81	0.07	0.02	0.49	2.85	0.07	0.02	0.50	2.83	0.07	0.02	0.49
2.56E+09	2.81	0.07	0.02	0.48	2.84	0.07	0.02	0.49	2.82	0.07	0.02	0.47
2.6E+09	2.81	0.07	0.02	0.50	2.84	0.06	0.02	0.51	2.81	0.06	0.02	0.51
2.68E+09	2.83	0.07	0.02	0.49	2.83	0.07	0.02	0.50	2.82	0.07	0.02	0.50
2.72E+09	2.82	0.07	0.03	0.46	2.84	0.07	0.02	0.47	2.82	0.07	0.03	0.45
2.8E+09	2.83	0.07	0.03	0.46	2.84	0.07	0.02	0.47	2.83	0.07	0.03	0.45
2.84E+09	2.83	0.07	0.02	0.48	2.85	0.07	0.02	0.49	2.83	0.07	0.02	0.48
2.92E+09	2.84	0.07	0.02	0.47	2.86	0.07	0.02	0.48	2.85	0.07	0.02	0.47
2.96E+09	2.82	0.07	0.02	0.47	2.84	0.07	0.02	0.47	2.82	0.07	0.03	0.46
3.04E+09	2.83	0.07	0.03	0.46	2.84	0.07	0.02	0.47	2.82	0.07	0.03	0.46
3.08E+09	2.84	0.07	0.03	0.46	2.86	0.07	0.03	0.46	2.85	0.07	0.03	0.45
3.16E+09	2.84	0.07	0.03	0.45	2.86	0.07	0.03	0.46	2.85	0.07	0.03	0.44
3.2E+09	2.84	0.07	0.03	0.46	2.86	0.07	0.02	0.47	2.84	0.07	0.03	0.46
3.28E+09	2.85	0.07	0.03	0.45	2.87	0.07	0.02	0.47	2.85	0.07	0.02	0.46
3.32E+09	2.84	0.07	0.03	0.44	2.86	0.07	0.03	0.44	2.85	0.08	0.03	0.43
3.4E+09	2.85	0.08	0.03	0.43	2.87	0.08	0.03	0.43	2.84	0.08	0.03	0.42
3.44E+09	2.84	0.07	0.03	0.45	2.88	0.07	0.03	0.45	2.86	0.07	0.03	0.44
3.52E+09	2.85	0.08	0.03	0.43	2.88	0.07	0.03	0.44	2.86	0.08	0.03	0.42
3.56E+09	2.85	0.08	0.03	0.44	2.86	0.07	0.03	0.44	2.84	0.08	0.03	0.44
3.64E+09	2.84	0.08	0.03	0.42	2.87	0.08	0.03	0.44	2.84	0.08	0.03	0.42
3.68E+09	2.85	0.08	0.03	0.42	2.88	0.08	0.03	0.42	2.86	0.08	0.03	0.42
3.76E+09	2.85	0.08	0.03	0.42	2.88	0.08	0.03	0.42	2.87	0.08	0.03	0.41
3.8E+09	2.86	0.08	0.03	0.42	2.89	0.08	0.03	0.43	2.87	0.08	0.03	0.42
3.88E+09	2.86	0.08	0.03	0.42	2.88	0.08	0.03	0.43	2.87	0.08	0.03	0.42
3.96E+09	2.85	0.08	0.03	0.41	2.89	0.08	0.03	0.42	2.85	0.08	0.03	0.40
4E+09	2.85	0.08	0.03	0.41	2.89	0.08	0.03	0.41	2.85	0.08	0.03	0.39

Table A-4: Dielectric properties for crude oil C2 blends with nC5

	nC5											
	10%				20%				50%			
frequency(Hz)	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp
3.22E+08	2.40	0.03	0.01	0.93	2.60	0.05	0.02	0.63	2.52	-0.05	-0.02	0.58
3.62E+08	2.55	0.03	0.01	1.10	2.69	0.05	0.02	0.65	2.57	-0.06	-0.02	0.54
4.42E+08	2.54	0.04	0.01	0.84	2.70	0.06	0.02	0.55	2.55	-0.02	-0.01	1.46
4.82E+08	2.48	0.03	0.01	1.11	2.63	0.06	0.02	0.57	2.55	-0.04	-0.02	0.74
5.62E+08	2.54	0.03	0.01	1.16	2.64	0.05	0.02	0.58	2.53	-0.05	-0.02	0.65
6.02E+08	2.49	0.03	0.01	1.04	2.64	0.06	0.02	0.50	2.53	0.02	0.01	1.34
6.82E+08	2.50	0.03	0.01	0.96	2.64	0.06	0.02	0.51	2.52	-0.01	0.00	4.29
7.22E+08	2.59	0.02	0.01	1.30	2.63	0.05	0.02	0.66	2.54	-0.04	-0.01	0.85
8.02E+08	2.59	0.04	0.01	0.83	2.64	0.05	0.02	0.61	2.54	-0.03	-0.01	1.08
8.42E+08	2.50	0.01	0.01	2.17	2.61	0.06	0.02	0.54	2.51	0.00	0.00	11.08
9.22E+08	2.51	0.03	0.01	1.22	2.62	0.06	0.02	0.54	2.53	0.01	0.00	4.24
9.62E+08	2.57	0.02	0.01	1.82	2.66	0.05	0.02	0.58	2.55	0.03	0.01	0.98
1.04E+09	2.57	0.01	0.01	2.17	2.65	0.06	0.02	0.56	2.53	0.02	0.01	1.38
1.08E+09	2.55	0.02	0.01	1.56	2.63	0.06	0.02	0.55	2.53	0.01	0.00	3.56
1.16E+09	2.57	0.01	0.00	2.65	2.62	0.06	0.02	0.56	2.54	-0.01	0.00	3.69
1.2E+09	2.55	0.02	0.01	1.24	2.64	0.06	0.02	0.54	2.52	0.02	0.01	1.28
1.28E+09	2.53	0.03	0.01	1.10	2.65	0.06	0.02	0.53	2.52	0.05	0.02	0.63
1.32E+09	2.60	0.02	0.01	1.68	2.64	0.05	0.02	0.59	2.54	0.00	0.00	15.55
1.4E+09	2.60	0.02	0.01	1.83	2.66	0.06	0.02	0.57	2.55	0.02	0.01	1.48
1.44E+09	2.52	0.02	0.01	1.83	2.64	0.06	0.02	0.50	2.52	0.04	0.02	0.76
1.52E+09	2.55	0.01	0.01	2.24	2.64	0.06	0.02	0.52	2.53	0.04	0.02	0.70
1.56E+09	2.60	0.02	0.01	1.66	2.66	0.06	0.02	0.56	2.55	0.03	0.01	1.12
1.64E+09	2.61	0.01	0.00	2.99	2.65	0.06	0.02	0.55	2.53	0.03	0.01	0.95
1.68E+09	2.58	0.04	0.01	0.89	2.64	0.06	0.02	0.51	2.54	0.04	0.02	0.72
1.76E+09	2.60	0.02	0.01	1.36	2.64	0.06	0.02	0.53	2.55	0.02	0.01	1.72
1.8E+09	2.58	0.01	0.00	3.13	2.66	0.06	0.02	0.52	2.54	0.05	0.02	0.59
1.88E+09	2.56	0.04	0.01	0.85	2.67	0.06	0.02	0.51	2.54	0.08	0.03	0.39
1.92E+09	2.62	0.03	0.01	1.03	2.65	0.06	0.02	0.54	2.57	0.03	0.01	1.09
2E+09	2.63	0.02	0.01	1.58	2.66	0.06	0.02	0.55	2.58	0.06	0.02	0.55
2.04E+09	2.58	0.02	0.01	1.39	2.67	0.06	0.02	0.51	2.55	0.09	0.04	0.33
2.12E+09	2.59	0.03	0.01	1.19	2.67	0.06	0.02	0.52	2.56	0.09	0.04	0.33
2.16E+09	2.66	0.03	0.01	1.09	2.69	0.06	0.02	0.56	2.57	0.10	0.04	0.31
2.24E+09	2.66	0.03	0.01	0.95	2.70	0.06	0.02	0.54	2.57	0.12	0.05	0.26

2.28E+09	2.63	0.04	0.02	0.78	2.69	0.06	0.02	0.52	2.57	0.11	0.04	0.28
2.36E+09	2.65	0.05	0.02	0.66	2.68	0.06	0.02	0.51	2.58	0.11	0.04	0.27
2.4E+09	2.63	0.06	0.02	0.54	2.64	0.06	0.02	0.49	2.57	0.16	0.06	0.19
2.44E+09	2.66	0.06	0.02	0.55	2.63	0.06	0.03	0.43	2.58	0.13	0.05	0.25
2.52E+09	2.66	0.05	0.02	0.58	2.69	0.06	0.02	0.50	2.59	0.14	0.05	0.23
2.56E+09	2.62	0.06	0.02	0.50	2.70	0.07	0.02	0.49	2.55	0.15	0.06	0.20
2.64E+09	2.64	0.06	0.02	0.53	2.71	0.06	0.02	0.50	2.58	0.14	0.05	0.23
2.68E+09	2.70	0.07	0.03	0.46	2.70	0.06	0.02	0.50	2.59	0.18	0.07	0.18
2.76E+09	2.69	0.07	0.03	0.47	2.71	0.07	0.02	0.49	2.59	0.17	0.07	0.18
2.8E+09	2.64	0.08	0.03	0.37	2.70	0.07	0.03	0.46	2.58	0.19	0.07	0.17
2.88E+09	2.64	0.08	0.03	0.39	2.69	0.07	0.03	0.47	2.58	0.20	0.08	0.16
2.92E+09	2.68	0.08	0.03	0.40	2.71	0.07	0.02	0.48	2.59	0.21	0.08	0.15
3E+09	2.66	0.08	0.03	0.38	2.72	0.07	0.02	0.47	2.58	0.21	0.08	0.15
3.04E+09	2.67	0.09	0.03	0.36	2.71	0.07	0.03	0.47	2.59	0.20	0.08	0.16
3.12E+09	2.70	0.10	0.04	0.33	2.71	0.07	0.03	0.47	2.60	0.21	0.08	0.15
3.16E+09	2.66	0.10	0.04	0.32	2.72	0.07	0.03	0.46	2.58	0.24	0.09	0.13
3.24E+09	2.65	0.10	0.04	0.31	2.72	0.07	0.03	0.45	2.57	0.25	0.10	0.12
3.28E+09	2.73	0.11	0.04	0.30	2.74	0.07	0.02	0.47	2.60	0.25	0.09	0.13
3.36E+09	2.73	0.11	0.04	0.29	2.73	0.07	0.03	0.46	2.61	0.25	0.10	0.13
3.4E+09	2.65	0.11	0.04	0.30	2.73	0.07	0.03	0.44	2.59	0.27	0.10	0.12
3.48E+09	2.64	0.12	0.05	0.26	2.72	0.07	0.03	0.44	2.59	0.29	0.11	0.11
3.52E+09	2.73	0.12	0.05	0.26	2.75	0.07	0.03	0.45	2.61	0.27	0.11	0.11
3.6E+09	2.68	0.12	0.05	0.26	2.71	0.07	0.03	0.44	2.58	0.32	0.12	0.10
3.64E+09	2.69	0.14	0.05	0.23	2.73	0.07	0.03	0.43	2.59	0.28	0.11	0.11
3.72E+09	2.72	0.13	0.05	0.24	2.74	0.07	0.03	0.44	2.60	0.31	0.12	0.10
3.76E+09	2.67	0.13	0.05	0.25	2.75	0.07	0.03	0.44	2.59	0.34	0.13	0.09
3.84E+09	2.68	0.13	0.05	0.24	2.78	0.08	0.03	0.43	2.58	0.36	0.14	0.09
3.88E+09	2.75	0.15	0.05	0.22	2.76	0.08	0.03	0.43	2.61	0.34	0.13	0.09
3.96E+09	2.75	0.15	0.06	0.21	2.76	0.08	0.03	0.43	2.62	0.36	0.14	0.09
4E+09	2.68	0.16	0.06	0.20	2.76	0.08	0.03	0.42	2.58	0.36	0.14	0.09

Table A-5: Dielectric properties for crude oil C2 blends with nC7

	nC7											
	10%				20%				50%			
frequency(Hz)	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp
3.22E+08	2.75	0.04	0.01	0.80	2.61	0.12	0.05	0.26	2.51	0.16	0.06	0.19
3.62E+08	2.77	0.08	0.03	0.42	2.64	0.13	0.05	0.25	2.56	0.16	0.06	0.19
4.42E+08	2.73	0.03	0.01	1.15	2.64	0.12	0.05	0.26	2.52	0.17	0.07	0.19
4.82E+08	2.69	-0.08	-0.03	0.41	2.63	0.12	0.05	0.26	2.58	0.15	0.06	0.21
5.62E+08	2.69	-0.06	-0.02	0.55	2.62	0.12	0.04	0.27	2.56	0.16	0.06	0.20
6.02E+08	2.67	0.02	0.01	1.48	2.62	0.13	0.05	0.25	2.50	0.17	0.07	0.18
6.82E+08	2.71	0.08	0.03	0.42	2.61	0.12	0.05	0.26	2.51	0.17	0.07	0.18
7.22E+08	2.75	0.04	0.01	0.79	2.64	0.12	0.05	0.27	2.60	0.16	0.06	0.19
8.02E+08	2.75	0.07	0.03	0.46	2.65	0.12	0.04	0.27	2.58	0.16	0.06	0.20
8.42E+08	2.72	0.11	0.04	0.29	2.61	0.12	0.04	0.27	2.50	0.16	0.06	0.19
9.22E+08	2.71	0.05	0.02	0.65	2.64	0.12	0.04	0.27	2.55	0.16	0.06	0.19
9.62E+08	2.72	0.03	0.01	1.06	2.65	0.12	0.05	0.26	2.56	0.16	0.06	0.19
1.04E+09	2.69	0.02	0.01	2.11	2.63	0.12	0.05	0.26	2.55	0.16	0.06	0.19
1.08E+09	2.69	0.00	0.00	30.07	2.64	0.12	0.05	0.27	2.55	0.16	0.06	0.19
1.16E+09	2.70	0.03	0.01	1.27	2.64	0.12	0.05	0.27	2.56	0.16	0.06	0.19
1.20E+09	2.70	0.07	0.02	0.49	2.63	0.12	0.05	0.26	2.54	0.17	0.07	0.18
1.28E+09	2.71	0.09	0.03	0.37	2.63	0.12	0.05	0.27	2.52	0.17	0.07	0.18
1.32E+09	2.74	0.06	0.02	0.58	2.65	0.12	0.05	0.26	2.58	0.16	0.06	0.19
1.40E+09	2.75	0.05	0.02	0.65	2.66	0.12	0.04	0.27	2.58	0.16	0.06	0.19
1.44E+09	2.72	0.05	0.02	0.66	2.64	0.12	0.05	0.27	2.52	0.16	0.07	0.19
1.52E+09	2.72	0.04	0.02	0.74	2.64	0.12	0.05	0.26	2.54	0.16	0.06	0.19
1.56E+09	2.72	0.04	0.02	0.77	2.66	0.12	0.05	0.26	2.58	0.17	0.06	0.19
1.64E+09	2.70	0.06	0.02	0.50	2.67	0.12	0.05	0.26	2.55	0.17	0.07	0.19
1.68E+09	2.71	0.05	0.02	0.71	2.65	0.12	0.05	0.26	2.56	0.16	0.06	0.19
1.76E+09	2.74	0.05	0.02	0.60	2.65	0.12	0.05	0.26	2.57	0.16	0.06	0.19
1.80E+09	2.73	0.11	0.04	0.28	2.65	0.12	0.05	0.26	2.54	0.17	0.07	0.19
1.88E+09	2.75	0.08	0.03	0.40	2.65	0.12	0.05	0.26	2.53	0.17	0.07	0.19
1.92E+09	2.77	0.06	0.02	0.55	2.66	0.12	0.04	0.27	2.60	0.16	0.06	0.19
2.00E+09	2.77	0.05	0.02	0.63	2.67	0.12	0.04	0.27	2.61	0.16	0.06	0.19
2.04E+09	2.74	0.07	0.02	0.50	2.67	0.12	0.05	0.26	2.56	0.17	0.06	0.19
2.12E+09	2.74	0.06	0.02	0.57	2.67	0.12	0.05	0.26	2.57	0.17	0.06	0.19
2.16E+09	2.76	0.06	0.02	0.53	2.68	0.12	0.05	0.26	2.60	0.17	0.06	0.19
2.24E+09	2.76	0.07	0.03	0.45	2.67	0.12	0.05	0.26	2.59	0.17	0.06	0.19

2.28E+09	2.76	0.08	0.03	0.43	2.67	0.12	0.05	0.26	2.60	0.17	0.06	0.19
2.36E+09	2.78	0.09	0.03	0.37	2.68	0.12	0.05	0.26	2.62	0.17	0.06	0.19
2.40E+09	2.78	0.10	0.03	0.34	2.67	0.13	0.05	0.25	2.60	0.17	0.07	0.18
2.44E+09	2.74	0.09	0.03	0.34	2.66	0.12	0.05	0.26	2.62	0.17	0.06	0.19
2.52E+09	2.80	0.10	0.04	0.33	2.68	0.12	0.05	0.26	2.63	0.17	0.06	0.19
2.56E+09	2.78	0.13	0.05	0.25	2.68	0.12	0.05	0.26	2.61	0.17	0.07	0.19
2.64E+09	2.76	0.15	0.05	0.22	2.68	0.13	0.05	0.25	2.59	0.17	0.07	0.18
2.68E+09	2.78	0.12	0.04	0.27	2.71	0.12	0.05	0.26	2.65	0.17	0.06	0.19
2.76E+09	2.79	0.12	0.04	0.28	2.72	0.12	0.05	0.26	2.64	0.17	0.06	0.19
2.80E+09	2.78	0.11	0.04	0.29	2.71	0.12	0.05	0.26	2.61	0.17	0.07	0.19
2.88E+09	2.79	0.13	0.05	0.24	2.71	0.12	0.05	0.26	2.62	0.17	0.07	0.18
2.92E+09	2.80	0.16	0.06	0.21	2.72	0.13	0.05	0.25	2.63	0.18	0.07	0.18
3.00E+09	2.81	0.18	0.06	0.19	2.72	0.13	0.05	0.25	2.63	0.18	0.07	0.18
3.04E+09	2.81	0.16	0.06	0.20	2.73	0.13	0.05	0.26	2.64	0.17	0.06	0.19
3.12E+09	2.81	0.17	0.06	0.19	2.73	0.13	0.05	0.25	2.66	0.17	0.06	0.19
3.16E+09	2.79	0.18	0.07	0.18	2.71	0.13	0.05	0.25	2.62	0.18	0.07	0.18
3.24E+09	2.79	0.16	0.06	0.20	2.72	0.13	0.05	0.25	2.62	0.18	0.07	0.18
3.28E+09	2.81	0.14	0.05	0.23	2.75	0.13	0.05	0.25	2.68	0.18	0.07	0.18
3.36E+09	2.79	0.16	0.06	0.20	2.76	0.13	0.05	0.25	2.67	0.18	0.07	0.18
3.40E+09	2.79	0.17	0.06	0.19	2.74	0.13	0.05	0.25	2.63	0.18	0.07	0.18
3.48E+09	2.80	0.20	0.07	0.16	2.74	0.13	0.05	0.24	2.64	0.18	0.07	0.18
3.52E+09	2.82	0.24	0.08	0.14	2.74	0.13	0.05	0.24	2.66	0.18	0.07	0.17
3.60E+09	2.83	0.25	0.09	0.13	2.74	0.14	0.05	0.24	2.64	0.18	0.07	0.18
3.64E+09	2.82	0.22	0.08	0.15	2.75	0.13	0.05	0.25	2.65	0.18	0.07	0.18
3.72E+09	2.84	0.22	0.08	0.15	2.75	0.13	0.05	0.24	2.67	0.18	0.07	0.18
3.76E+09	2.79	0.25	0.09	0.13	2.74	0.14	0.05	0.24	2.64	0.18	0.07	0.17
3.84E+09	2.80	0.24	0.08	0.14	2.74	0.14	0.05	0.24	2.64	0.18	0.07	0.17
3.88E+09	2.84	0.23	0.08	0.14	2.75	0.14	0.05	0.24	2.69	0.18	0.07	0.18
3.96E+09	2.83	0.26	0.09	0.13	2.77	0.14	0.05	0.23	2.69	0.18	0.07	0.17
4.00E+09	2.81	0.27	0.09	0.12	2.74	0.14	0.05	0.23	2.64	0.18	0.07	0.17

Table A-6: Dielectric properties for crude oil C2 blends with Toluene

	Toluene											
	10%				20%				50%			
frequency(Hz)	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp
3.22E+08	2.72	0.06	0.02	0.55	2.74	0.05	0.02	0.60	2.75	0.05	0.02	0.61
3.62E+08	2.75	0.06	0.02	0.58	2.84	0.05	0.02	0.63	2.86	0.05	0.02	0.68
4.42E+08	2.75	0.06	0.02	0.56	2.79	0.06	0.02	0.57	2.80	0.06	0.02	0.57
4.82E+08	2.74	0.06	0.02	0.53	2.77	0.05	0.02	0.61	2.74	0.05	0.02	0.61
5.62E+08	2.73	0.06	0.02	0.56	2.75	0.05	0.02	0.62	2.75	0.05	0.02	0.67
6.02E+08	2.73	0.06	0.02	0.56	2.78	0.06	0.02	0.54	2.78	0.06	0.02	0.52
6.82E+08	2.74	0.06	0.02	0.57	2.76	0.06	0.02	0.55	2.76	0.06	0.02	0.53
7.22E+08	2.74	0.06	0.02	0.55	2.76	0.05	0.02	0.64	2.77	0.05	0.02	0.65
8.02E+08	2.72	0.06	0.02	0.57	2.77	0.05	0.02	0.63	2.77	0.05	0.02	0.67
8.42E+08	2.73	0.06	0.02	0.54	2.76	0.06	0.02	0.52	2.76	0.06	0.02	0.50
9.22E+08	2.74	0.06	0.02	0.52	2.77	0.06	0.02	0.51	2.75	0.06	0.02	0.52
9.62E+08	2.75	0.06	0.02	0.54	2.78	0.06	0.02	0.56	2.79	0.05	0.02	0.60
1.04E+09	2.75	0.06	0.02	0.52	2.77	0.06	0.02	0.54	2.78	0.06	0.02	0.54
1.08E+09	2.74	0.06	0.02	0.52	2.75	0.06	0.02	0.54	2.74	0.06	0.02	0.55
1.16E+09	2.74	0.06	0.02	0.53	2.75	0.06	0.02	0.56	2.74	0.06	0.02	0.56
1.20E+09	2.74	0.06	0.02	0.53	2.77	0.06	0.02	0.54	2.78	0.06	0.02	0.52
1.28E+09	2.74	0.06	0.02	0.51	2.77	0.06	0.02	0.52	2.77	0.06	0.02	0.51
1.32E+09	2.73	0.06	0.02	0.54	2.76	0.06	0.02	0.57	2.76	0.05	0.02	0.59
1.40E+09	2.74	0.06	0.02	0.54	2.77	0.06	0.02	0.56	2.78	0.06	0.02	0.58
1.44E+09	2.74	0.06	0.02	0.51	2.77	0.07	0.02	0.50	2.76	0.07	0.02	0.47
1.52E+09	2.75	0.06	0.02	0.51	2.77	0.06	0.02	0.50	2.76	0.07	0.02	0.49
1.56E+09	2.76	0.06	0.02	0.52	2.78	0.06	0.02	0.56	2.78	0.06	0.02	0.56
1.64E+09	2.75	0.06	0.02	0.51	2.77	0.06	0.02	0.56	2.77	0.06	0.02	0.56
1.68E+09	2.74	0.06	0.02	0.51	2.76	0.06	0.02	0.52	2.74	0.06	0.02	0.52
1.76E+09	2.76	0.06	0.02	0.52	2.76	0.06	0.02	0.53	2.76	0.06	0.02	0.51
1.80E+09	2.75	0.06	0.02	0.52	2.77	0.06	0.02	0.51	2.77	0.06	0.02	0.51
1.88E+09	2.78	0.06	0.02	0.52	2.80	0.06	0.02	0.52	2.78	0.06	0.02	0.52
1.92E+09	2.76	0.06	0.02	0.54	2.78	0.06	0.02	0.55	2.77	0.06	0.02	0.56
2.00E+09	2.78	0.06	0.02	0.54	2.80	0.06	0.02	0.56	2.79	0.06	0.02	0.56
2.04E+09	2.79	0.06	0.02	0.52	2.81	0.06	0.02	0.52	2.80	0.06	0.02	0.50
2.12E+09	2.79	0.06	0.02	0.51	2.80	0.06	0.02	0.51	2.80	0.07	0.02	0.49
2.16E+09	2.79	0.06	0.02	0.52	2.82	0.06	0.02	0.54	2.80	0.06	0.02	0.54
2.24E+09	2.81	0.06	0.02	0.51	2.83	0.06	0.02	0.54	2.81	0.06	0.02	0.54
2.28E+09	2.79	0.06	0.02	0.51	2.81	0.06	0.02	0.51	2.79	0.07	0.02	0.50

2.36E+09	2.80	0.06	0.02	0.50	2.81	0.06	0.02	0.52	2.79	0.07	0.02	0.50
2.40E+09	2.80	0.06	0.02	0.51	2.82	0.06	0.02	0.52	2.83	0.07	0.02	0.50
2.44E+09	2.79	0.06	0.02	0.50	2.79	0.07	0.02	0.50	2.79	0.06	0.02	0.50
2.52E+09	2.80	0.07	0.02	0.49	2.82	0.07	0.02	0.50	2.81	0.06	0.02	0.51
2.56E+09	2.81	0.07	0.02	0.48	2.84	0.07	0.02	0.49	2.82	0.07	0.02	0.47
2.64E+09	2.83	0.07	0.02	0.50	2.85	0.07	0.02	0.50	2.83	0.07	0.02	0.47
2.68E+09	2.83	0.07	0.02	0.49	2.83	0.07	0.02	0.50	2.82	0.07	0.02	0.50
2.76E+09	2.83	0.07	0.02	0.49	2.85	0.06	0.02	0.51	2.84	0.07	0.02	0.50
2.80E+09	2.83	0.07	0.03	0.46	2.84	0.07	0.02	0.47	2.83	0.07	0.03	0.45
2.88E+09	2.82	0.07	0.02	0.47	2.83	0.07	0.02	0.47	2.82	0.07	0.03	0.45
2.92E+09	2.84	0.07	0.02	0.47	2.86	0.07	0.02	0.48	2.85	0.07	0.02	0.47
3.00E+09	2.84	0.07	0.02	0.47	2.86	0.07	0.02	0.47	2.85	0.07	0.03	0.45
3.04E+09	2.83	0.07	0.03	0.46	2.84	0.07	0.02	0.47	2.82	0.07	0.03	0.46
3.12E+09	2.83	0.07	0.03	0.46	2.85	0.07	0.02	0.47	2.83	0.07	0.03	0.46
3.16E+09	2.84	0.07	0.03	0.45	2.86	0.07	0.03	0.46	2.85	0.07	0.03	0.44
3.24E+09	2.84	0.07	0.03	0.45	2.86	0.07	0.03	0.45	2.85	0.08	0.03	0.43
3.28E+09	2.85	0.07	0.03	0.45	2.87	0.07	0.02	0.47	2.85	0.07	0.02	0.46
3.36E+09	2.84	0.07	0.03	0.45	2.85	0.07	0.03	0.46	2.84	0.07	0.03	0.44
3.40E+09	2.85	0.08	0.03	0.43	2.87	0.08	0.03	0.43	2.84	0.08	0.03	0.42
3.48E+09	2.83	0.08	0.03	0.43	2.85	0.08	0.03	0.44	2.83	0.08	0.03	0.42
3.52E+09	2.85	0.08	0.03	0.43	2.88	0.07	0.03	0.44	2.86	0.08	0.03	0.42
3.60E+09	2.85	0.08	0.03	0.43	2.90	0.08	0.03	0.44	2.88	0.08	0.03	0.42
3.64E+09	2.84	0.08	0.03	0.42	2.87	0.08	0.03	0.44	2.84	0.08	0.03	0.42
3.72E+09	2.87	0.08	0.03	0.43	2.87	0.08	0.03	0.43	2.87	0.08	0.03	0.43
3.76E+09	2.85	0.08	0.03	0.42	2.88	0.08	0.03	0.42	2.87	0.08	0.03	0.41
3.84E+09	2.89	0.08	0.03	0.42	2.89	0.08	0.03	0.42	2.90	0.08	0.03	0.41
3.88E+09	2.86	0.08	0.03	0.42	2.88	0.08	0.03	0.43	2.87	0.08	0.03	0.42
3.96E+09	2.85	0.08	0.03	0.41	2.89	0.08	0.03	0.42	2.85	0.08	0.03	0.40
4.00E+09	2.85	0.08	0.03	0.41	2.89	0.08	0.03	0.41	2.85	0.08	0.03	0.39

Table A-7: Dielectric properties for crude oil C3 blends with nC5

	nC5											
	10%				20%				50%			
frequency(Hz)	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp
3.22E+08	2.46	-0.03	-0.01	1.13	2.62	0.17	0.06	0.19	2.68	0.08	0.03	0.41
3.62E+08	2.39	0.05	0.02	0.57	2.65	0.10	0.04	0.30	2.62	0.07	0.03	0.44
4.42E+08	2.39	0.02	0.01	1.72	2.64	0.08	0.03	0.38	2.63	0.00	0.00	11.63
4.82E+08	2.48	0.01	0.00	3.31	2.59	0.02	0.01	1.78	2.63	0.09	0.03	0.36
5.62E+08	2.50	0.06	0.02	0.52	2.57	0.03	0.01	1.24	2.60	0.04	0.02	0.70
6.02E+08	2.42	-0.03	-0.01	0.92	2.60	0.08	0.03	0.40	2.63	-0.07	-0.03	0.43
6.82E+08	2.42	-0.07	-0.03	0.45	2.58	0.10	0.04	0.30	2.65	-0.06	-0.02	0.53
7.22E+08	2.45	0.01	0.00	4.27	2.58	0.07	0.03	0.42	2.59	0.05	0.02	0.60
8.02E+08	2.45	0.03	0.01	1.18	2.56	0.08	0.03	0.37	2.61	0.05	0.02	0.64
8.42E+08	2.44	-0.04	-0.01	0.84	2.56	0.15	0.06	0.21	2.67	-0.01	0.00	2.90
9.22E+08	2.46	-0.05	-0.02	0.64	2.55	0.11	0.04	0.29	2.64	0.00	0.00	8.96
9.62E+08	2.45	0.01	0.01	2.33	2.57	0.08	0.03	0.41	2.61	0.02	0.01	2.09
1.04E+09	2.44	0.01	0.00	2.76	2.59	0.04	0.02	0.72	2.61	-0.02	-0.01	1.39
1.08E+09	2.48	-0.01	-0.01	2.10	2.58	0.04	0.02	0.71	2.62	0.01	0.00	3.50
1.16E+09	2.48	-0.01	0.00	5.97	2.57	0.04	0.02	0.76	2.61	0.00	0.00	17.97
1.2E+09	2.43	-0.02	-0.01	1.58	2.57	0.06	0.02	0.49	2.62	-0.05	-0.02	0.63
1.28E+09	2.44	-0.01	-0.01	2.21	2.55	0.07	0.03	0.42	2.65	-0.04	-0.01	0.81
1.32E+09	2.48	0.01	0.00	5.52	2.55	0.05	0.02	0.57	2.61	0.01	0.01	2.28
1.4E+09	2.47	0.04	0.02	0.82	2.53	0.06	0.02	0.56	2.60	0.01	0.00	2.69
1.44E+09	2.44	-0.01	0.00	3.39	2.55	0.06	0.02	0.54	2.65	-0.02	-0.01	1.60
1.52E+09	2.47	-0.01	0.00	2.68	2.57	0.06	0.02	0.51	2.64	-0.03	-0.01	1.22
1.56E+09	2.46	0.04	0.02	0.78	2.58	0.04	0.02	0.79	2.61	-0.02	-0.01	1.35
1.64E+09	2.46	0.04	0.02	0.82	2.58	0.03	0.01	0.92	2.62	-0.04	-0.01	0.86
1.68E+09	2.47	0.02	0.01	1.64	2.60	0.04	0.02	0.80	2.63	-0.01	0.00	3.48
1.76E+09	2.49	0.02	0.01	1.75	2.58	0.04	0.02	0.76	2.63	-0.02	-0.01	1.65
1.8E+09	2.44	0.03	0.01	1.03	2.56	0.04	0.02	0.72	2.65	-0.06	-0.02	0.53
1.88E+09	2.43	0.02	0.01	1.41	2.58	0.07	0.03	0.44	2.66	-0.04	-0.01	0.80
1.92E+09	2.48	0.03	0.01	1.13	2.55	0.04	0.02	0.81	2.63	0.00	0.00	8.93
2E+09	2.48	0.04	0.02	0.79	2.57	0.04	0.02	0.80	2.62	0.00	0.00	61.04
2.04E+09	2.45	0.02	0.01	1.95	2.57	0.05	0.02	0.57	2.67	-0.04	-0.02	0.73
2.12E+09	2.48	0.02	0.01	1.55	2.60	0.05	0.02	0.60	2.67	-0.04	-0.01	0.90
2.16E+09	2.49	0.05	0.02	0.59	2.61	0.04	0.01	0.83	2.64	-0.03	-0.01	1.09
2.24E+09	2.49	0.07	0.03	0.43	2.61	0.04	0.02	0.75	2.64	-0.03	-0.01	1.23

2.28E+09	2.50	0.04	0.02	0.76	2.61	0.05	0.02	0.66	2.67	-0.02	-0.01	1.80
2.36E+09	2.49	0.05	0.02	0.58	2.59	0.04	0.02	0.71	2.67	0.00	0.00	53.27
2.4E+09	2.48	0.06	0.02	0.50	2.61	0.06	0.02	0.55	2.67	0.00	0.00	13.38
2.44E+09	2.50	0.06	0.03	0.48	2.58	0.05	0.02	0.67	2.66	0.03	0.01	1.11
2.52E+09	2.50	0.08	0.03	0.40	2.60	0.05	0.02	0.63	2.65	0.02	0.01	1.46
2.56E+09	2.47	0.07	0.03	0.41	2.59	0.07	0.03	0.47	2.71	-0.03	-0.01	1.14
2.64E+09	2.48	0.07	0.03	0.46	2.63	0.05	0.02	0.66	2.69	0.00	0.00	12.80
2.68E+09	2.50	0.09	0.04	0.33	2.64	0.06	0.02	0.50	2.65	0.01	0.00	5.49
2.76E+09	2.51	0.12	0.05	0.25	2.66	0.05	0.02	0.69	2.65	0.01	0.00	2.73
2.8E+09	2.50	0.09	0.03	0.36	2.65	0.08	0.03	0.39	2.70	0.00	0.00	20.73
2.88E+09	2.50	0.09	0.03	0.36	2.65	0.08	0.03	0.38	2.70	0.03	0.01	1.19
2.92E+09	2.50	0.11	0.04	0.28	2.65	0.07	0.03	0.43	2.68	0.01	0.00	3.02
2.96E+09	2.50	0.10	0.04	0.31	2.63	0.07	0.03	0.46	2.70	0.05	0.02	0.66
3.04E+09	2.51	0.11	0.04	0.29	2.64	0.07	0.03	0.46	2.69	0.05	0.02	0.61
3.08E+09	2.48	0.12	0.05	0.26	2.64	0.08	0.03	0.38	2.70	0.02	0.01	1.86
3.16E+09	2.49	0.12	0.05	0.26	2.65	0.10	0.04	0.33	2.70	0.02	0.01	1.61
3.2E+09	2.52	0.13	0.05	0.24	2.66	0.10	0.04	0.32	2.66	0.06	0.02	0.58
3.28E+09	2.54	0.13	0.05	0.24	2.67	0.10	0.04	0.30	2.67	0.04	0.02	0.71
3.32E+09	2.50	0.12	0.05	0.25	2.66	0.12	0.04	0.27	2.71	0.03	0.01	0.96
3.4E+09	2.51	0.13	0.05	0.23	2.67	0.13	0.05	0.25	2.72	0.05	0.02	0.71
3.44E+09	2.52	0.14	0.06	0.22	2.67	0.09	0.03	0.36	2.70	0.06	0.02	0.57
3.52E+09	2.51	0.16	0.06	0.20	2.65	0.12	0.04	0.27	2.70	0.05	0.02	0.70
3.56E+09	2.53	0.14	0.06	0.22	2.67	0.12	0.04	0.27	2.72	0.08	0.03	0.39
3.64E+09	2.51	0.15	0.06	0.20	2.66	0.12	0.05	0.25	2.71	0.09	0.03	0.37
3.68E+09	2.50	0.18	0.07	0.17	2.66	0.13	0.05	0.24	2.71	0.06	0.02	0.53
3.76E+09	2.51	0.16	0.07	0.19	2.68	0.15	0.05	0.22	2.71	0.07	0.03	0.46
3.8E+09	2.53	0.18	0.07	0.18	2.68	0.15	0.06	0.21	2.68	0.08	0.03	0.42
3.88E+09	2.54	0.18	0.07	0.18	2.68	0.15	0.06	0.21	2.68	0.07	0.03	0.43
3.92E+09	2.52	0.19	0.08	0.16	2.66	0.17	0.06	0.19	2.74	0.05	0.02	0.62
4E+09	2.50	0.18	0.07	0.18	2.68	0.16	0.06	0.20	2.75	0.08	0.03	0.43

Table A-8: Dielectric properties for crude oil C3 blends with nC7

	nC7											
	10%				20%				50%			
frequency(Hz)	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp
3.22E+08	2.75	0.19	0.07	0.17	2.86	-0.06	-0.02	0.52	3.21	-0.04	-0.01	0.98
3.62E+08	2.70	0.19	0.07	0.16	2.86	-0.04	-0.02	0.74	3.18	-0.03	-0.01	1.03
4.42E+08	2.67	0.06	0.02	0.52	2.87	-0.01	0.00	5.75	3.17	-0.06	-0.02	0.57
4.82E+08	2.73	0.02	0.01	1.30	2.86	-0.03	-0.01	1.22	3.15	-0.07	-0.02	0.47
5.62E+08	2.72	0.01	0.00	4.46	2.84	-0.05	-0.02	0.64	3.14	-0.07	-0.02	0.51
6.02E+08	2.67	-0.02	-0.01	1.54	2.84	-0.06	-0.02	0.58	3.10	-0.11	-0.03	0.33
6.82E+08	2.68	-0.01	0.00	2.82	2.84	-0.07	-0.02	0.50	3.09	-0.09	-0.03	0.37
7.22E+08	2.72	0.06	0.02	0.54	2.85	-0.06	-0.02	0.55	3.10	-0.05	-0.02	0.66
8.02E+08	2.73	0.11	0.04	0.29	2.84	-0.04	-0.02	0.75	3.14	-0.03	-0.01	1.09
8.42E+08	2.73	0.04	0.01	0.80	2.83	-0.05	-0.02	0.73	3.10	-0.05	-0.02	0.71
9.22E+08	2.70	0.02	0.01	1.49	2.84	-0.03	-0.01	1.16	3.13	-0.08	-0.03	0.43
9.62E+08	2.73	0.05	0.02	0.68	2.84	-0.03	-0.01	0.95	3.07	-0.07	-0.02	0.47
1.04E+09	2.69	0.00	0.00	7.60	2.84	-0.02	-0.01	2.04	3.07	-0.08	-0.03	0.44
1.08E+09	2.72	-0.02	-0.01	1.30	2.84	-0.02	-0.01	1.54	3.09	-0.07	-0.02	0.46
1.16E+09	2.73	-0.02	-0.01	1.50	2.85	-0.04	-0.01	0.88	3.10	-0.06	-0.02	0.54
1.2E+09	2.69	-0.02	-0.01	1.68	2.83	-0.04	-0.01	0.78	3.09	-0.06	-0.02	0.54
1.28E+09	2.71	-0.01	0.00	6.34	2.85	-0.03	-0.01	1.08	3.10	-0.05	-0.02	0.65
1.32E+09	2.74	0.04	0.02	0.72	2.85	-0.04	-0.02	0.76	3.09	-0.03	-0.01	1.00
1.4E+09	2.73	0.05	0.02	0.66	2.86	-0.03	-0.01	1.25	3.11	-0.05	-0.02	0.67
1.44E+09	2.71	0.00	0.00	9.94	2.85	-0.03	-0.01	1.04	3.09	-0.06	-0.02	0.59
1.52E+09	2.72	-0.02	-0.01	1.43	2.87	-0.03	-0.01	1.01	3.09	-0.07	-0.02	0.53
1.56E+09	2.72	0.00	0.00	14.40	2.88	-0.03	-0.01	0.95	3.09	-0.06	-0.02	0.59
1.64E+09	2.71	-0.02	-0.01	1.69	2.87	0.00	0.00	390.94	3.10	-0.06	-0.02	0.56
1.68E+09	2.74	-0.02	-0.01	1.48	2.86	-0.04	-0.01	0.84	3.10	-0.02	-0.01	1.67
1.76E+09	2.75	-0.03	-0.01	1.02	2.87	-0.01	0.00	3.19	3.08	-0.04	-0.01	0.81
1.8E+09	2.74	-0.03	-0.01	1.17	2.87	-0.02	-0.01	1.74	3.12	-0.05	-0.02	0.71
1.88E+09	2.74	0.00	0.00	113.60	2.87	-0.02	-0.01	1.42	3.09	-0.06	-0.02	0.62
1.92E+09	2.76	0.01	0.00	2.43	2.88	-0.01	0.00	5.29	3.10	-0.02	-0.01	1.58
2E+09	2.76	0.02	0.01	2.12	2.88	0.00	0.00	8.86	3.09	-0.02	-0.01	1.55
2.04E+09	2.75	-0.03	-0.01	1.02	2.87	0.01	0.00	4.18	3.10	-0.03	-0.01	1.04
2.12E+09	2.76	-0.05	-0.02	0.68	2.88	0.01	0.00	4.93	3.09	-0.03	-0.01	1.25
2.16E+09	2.77	-0.02	-0.01	1.37	2.88	0.01	0.00	3.60	3.11	-0.02	-0.01	1.94
2.24E+09	2.76	-0.01	0.00	2.47	2.90	0.01	0.00	3.74	3.13	-0.01	0.00	3.69

2.28E+09	2.78	-0.04	-0.01	0.89	2.89	0.00	0.00	15.02	3.13	0.00	0.00	8.96
2.36E+09	2.79	-0.01	0.00	3.69	2.89	0.01	0.00	5.05	3.14	0.01	0.00	2.45
2.4E+09	2.77	0.03	0.01	1.08	2.89	0.03	0.01	0.99	3.14	0.01	0.00	5.40
2.44E+09	2.79	0.03	0.01	1.11	2.91	0.02	0.01	2.02	3.12	0.01	0.00	4.00
2.52E+09	2.80	0.03	0.01	1.25	2.90	0.02	0.01	2.03	3.12	0.01	0.00	2.88
2.56E+09	2.79	0.00	0.00	6.73	2.91	0.02	0.01	1.80	3.13	0.00	0.00	13.72
2.64E+09	2.77	0.01	0.00	3.17	2.91	0.02	0.01	1.48	3.16	0.01	0.00	6.28
2.68E+09	2.80	0.00	0.00	7.42	2.94	0.03	0.01	1.20	3.16	0.03	0.01	1.08
2.76E+09	2.79	0.01	0.00	2.65	2.92	0.04	0.01	0.85	3.17	0.06	0.02	0.62
2.8E+09	2.81	-0.02	-0.01	1.83	2.93	0.03	0.01	1.07	3.18	0.05	0.02	0.70
2.88E+09	2.81	0.01	0.00	2.50	2.92	0.05	0.02	0.73	3.19	0.07	0.02	0.49
2.92E+09	2.80	0.04	0.01	0.83	2.93	0.06	0.02	0.52	3.18	0.08	0.03	0.42
2.96E+09	2.82	0.04	0.01	0.86	2.93	0.05	0.02	0.61	3.18	0.07	0.02	0.48
3.04E+09	2.82	0.05	0.02	0.65	2.94	0.06	0.02	0.53	3.18	0.08	0.03	0.43
3.08E+09	2.80	0.05	0.02	0.66	2.95	0.08	0.03	0.43	3.17	0.08	0.03	0.42
3.16E+09	2.80	0.04	0.01	0.83	2.95	0.08	0.03	0.40	3.18	0.09	0.03	0.37
3.2E+09	2.81	0.06	0.02	0.59	2.94	0.09	0.03	0.39	3.18	0.11	0.03	0.33
3.28E+09	2.80	0.04	0.01	0.93	2.93	0.08	0.03	0.42	3.18	0.12	0.04	0.30
3.32E+09	2.80	0.02	0.01	1.35	2.95	0.09	0.03	0.37	3.20	0.12	0.04	0.29
3.4E+09	2.80	0.03	0.01	0.96	2.96	0.09	0.03	0.36	3.22	0.15	0.05	0.24
3.44E+09	2.83	0.06	0.02	0.51	2.95	0.11	0.04	0.31	3.20	0.16	0.05	0.21
3.52E+09	2.82	0.10	0.03	0.34	2.97	0.11	0.04	0.30	3.21	0.16	0.05	0.22
3.56E+09	2.83	0.07	0.02	0.48	2.95	0.14	0.05	0.24	3.18	0.16	0.05	0.22
3.64E+09	2.83	0.08	0.03	0.43	2.96	0.13	0.04	0.27	3.21	0.17	0.05	0.20
3.68E+09	2.81	0.09	0.03	0.35	2.95	0.13	0.04	0.25	3.20	0.17	0.05	0.20
3.76E+09	2.81	0.09	0.03	0.35	2.97	0.15	0.05	0.22	3.22	0.17	0.05	0.21
3.8E+09	2.82	0.07	0.02	0.47	2.97	0.14	0.05	0.24	3.20	0.20	0.06	0.18
3.88E+09	2.84	0.07	0.03	0.45	2.98	0.14	0.05	0.23	3.22	0.21	0.07	0.16
3.92E+09	2.86	0.06	0.02	0.53	2.99	0.16	0.05	0.21	3.14	0.19	0.06	0.18
4E+09	2.83	0.07	0.02	0.48	2.99	0.17	0.06	0.20	3.20	0.25	0.08	0.14

Table A-9: Dielectric properties for crude oil C3 blends with Toluene

	Toluene											
	10%				20%				50%			
frequency(Hz)	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp	e'	e"	(e"/e')	Dp
3.22E+08	2.65	-0.04	-0.02	0.71	2.69	0.06	0.02	0.54	2.70	-0.08	-0.03	0.38
3.62E+08	2.66	0.03	0.01	1.18	2.69	0.08	0.03	0.42	2.66	-0.06	-0.02	0.56
4.42E+08	2.64	0.01	0.00	3.96	2.66	0.02	0.01	1.59	2.63	0.00	0.00	9.94
4.82E+08	2.64	-0.02	-0.01	1.65	2.68	-0.03	-0.01	1.01	2.70	-0.01	0.00	4.13
5.62E+08	2.64	0.01	0.00	4.26	2.66	-0.02	-0.01	1.65	2.69	-0.02	-0.01	1.74
6.02E+08	2.64	0.04	0.01	0.85	2.65	0.04	0.02	0.70	2.63	-0.01	0.00	2.51
6.82E+08	2.64	0.04	0.02	0.75	2.68	0.07	0.03	0.45	2.67	-0.01	0.00	4.07
7.22E+08	2.68	0.02	0.01	1.33	2.74	0.04	0.01	0.86	2.67	0.03	0.01	1.02
8.02E+08	2.66	0.01	0.00	4.77	2.72	0.03	0.01	1.22	2.66	0.01	0.00	4.06
8.42E+08	2.67	0.01	0.00	4.10	2.72	0.06	0.02	0.56	2.70	0.01	0.00	3.58
9.22E+08	2.65	-0.01	0.00	2.47	2.68	0.02	0.01	1.45	2.68	0.02	0.01	1.31
9.62E+08	2.65	0.01	0.00	4.88	2.69	0.03	0.01	1.25	2.66	0.02	0.01	1.33
1.04E+09	2.65	0.01	0.01	2.22	2.69	0.02	0.01	1.53	2.68	0.04	0.01	0.85
1.08E+09	2.65	0.01	0.01	2.39	2.69	0.01	0.00	4.75	2.69	0.04	0.01	0.89
1.16E+09	2.66	0.01	0.00	2.60	2.70	0.02	0.01	1.63	2.69	0.04	0.02	0.72
1.2E+09	2.64	0.02	0.01	1.86	2.69	0.05	0.02	0.61	2.68	0.04	0.02	0.75
1.28E+09	2.66	0.02	0.01	1.98	2.72	0.05	0.02	0.60	2.67	0.04	0.02	0.71
1.32E+09	2.67	0.00	0.00	7.96	2.75	0.04	0.01	0.82	2.69	0.05	0.02	0.67
1.4E+09	2.68	0.01	0.01	2.13	2.73	0.04	0.01	0.83	2.70	0.06	0.02	0.55
1.44E+09	2.64	0.01	0.00	3.30	2.70	0.03	0.01	0.98	2.69	0.05	0.02	0.59
1.52E+09	2.67	0.01	0.01	2.19	2.71	0.03	0.01	0.99	2.69	0.06	0.02	0.52
1.56E+09	2.67	0.01	0.00	3.18	2.74	0.02	0.01	1.51	2.69	0.05	0.02	0.62
1.64E+09	2.66	0.00	0.00	10.79	2.72	0.02	0.01	1.57	2.71	0.07	0.02	0.49
1.68E+09	2.66	0.01	0.00	4.69	2.73	0.02	0.01	1.49	2.71	0.06	0.02	0.54
1.76E+09	2.65	0.03	0.01	1.03	2.73	0.04	0.01	0.81	2.71	0.07	0.03	0.45
1.8E+09	2.64	0.03	0.01	1.24	2.73	0.04	0.01	0.80	2.72	0.07	0.03	0.44
1.88E+09	2.65	0.05	0.02	0.62	2.73	0.07	0.03	0.46	2.72	0.08	0.03	0.41
1.92E+09	2.66	0.03	0.01	0.96	2.75	0.05	0.02	0.65	2.73	0.08	0.03	0.40
2E+09	2.66	0.04	0.01	0.90	2.74	0.05	0.02	0.63	2.73	0.09	0.03	0.38
2.04E+09	2.66	0.04	0.01	0.88	2.73	0.06	0.02	0.56	2.73	0.09	0.03	0.37
2.12E+09	2.67	0.04	0.01	0.82	2.73	0.05	0.02	0.59	2.74	0.10	0.04	0.32
2.16E+09	2.68	0.05	0.02	0.67	2.75	0.04	0.02	0.78	2.75	0.10	0.04	0.31
2.24E+09	2.69	0.04	0.02	0.74	2.74	0.05	0.02	0.63	2.75	0.11	0.04	0.30

2.28E+09	2.69	0.04	0.02	0.77	2.75	0.05	0.02	0.60	2.75	0.12	0.04	0.27
2.36E+09	2.70	0.04	0.02	0.76	2.75	0.06	0.02	0.56	2.75	0.12	0.04	0.26
2.4E+09	2.70	0.05	0.02	0.59	2.75	0.07	0.03	0.44	2.74	0.14	0.05	0.23
2.44E+09	2.70	0.05	0.02	0.71	2.74	0.07	0.02	0.48	2.75	0.13	0.05	0.24
2.52E+09	2.71	0.04	0.02	0.75	2.77	0.06	0.02	0.55	2.76	0.14	0.05	0.23
2.56E+09	2.70	0.07	0.02	0.49	2.75	0.09	0.03	0.36	2.74	0.14	0.05	0.23
2.64E+09	2.71	0.03	0.01	0.94	2.76	0.05	0.02	0.61	2.75	0.15	0.05	0.22
2.68E+09	2.71	0.07	0.02	0.49	2.78	0.07	0.03	0.43	2.75	0.16	0.06	0.21
2.76E+09	2.72	0.06	0.02	0.56	2.78	0.07	0.03	0.45	2.76	0.16	0.06	0.20
2.8E+09	2.71	0.06	0.02	0.50	2.76	0.08	0.03	0.40	2.77	0.16	0.06	0.20
2.88E+09	2.72	0.05	0.02	0.59	2.77	0.07	0.03	0.45	2.77	0.17	0.06	0.19
2.92E+09	2.74	0.08	0.03	0.40	2.79	0.09	0.03	0.36	2.77	0.17	0.06	0.19
2.96E+09	2.73	0.06	0.02	0.56	2.79	0.07	0.03	0.44	2.77	0.18	0.06	0.18
3.04E+09	2.74	0.07	0.03	0.44	2.80	0.09	0.03	0.36	2.77	0.19	0.07	0.17
3.08E+09	2.74	0.09	0.03	0.38	2.79	0.11	0.04	0.29	2.77	0.19	0.07	0.17
3.16E+09	2.74	0.10	0.04	0.33	2.80	0.12	0.04	0.28	2.77	0.20	0.07	0.17
3.2E+09	2.74	0.09	0.03	0.36	2.82	0.10	0.04	0.31	2.79	0.21	0.07	0.16
3.28E+09	2.73	0.10	0.04	0.31	2.80	0.11	0.04	0.29	2.79	0.23	0.08	0.14
3.32E+09	2.73	0.11	0.04	0.29	2.79	0.13	0.04	0.26	2.77	0.22	0.08	0.15
3.4E+09	2.72	0.10	0.04	0.31	2.79	0.12	0.04	0.27	2.78	0.23	0.08	0.14
3.44E+09	2.75	0.12	0.04	0.27	2.82	0.13	0.05	0.25	2.78	0.22	0.08	0.14
3.52E+09	2.76	0.12	0.04	0.27	2.82	0.14	0.05	0.23	2.81	0.25	0.09	0.13
3.56E+09	2.74	0.10	0.04	0.31	2.79	0.12	0.04	0.27	2.80	0.23	0.08	0.14
3.64E+09	2.76	0.12	0.04	0.28	2.82	0.14	0.05	0.23	2.81	0.24	0.09	0.13
3.68E+09	2.76	0.16	0.06	0.20	2.81	0.19	0.07	0.17	2.80	0.25	0.09	0.13
3.76E+09	2.76	0.15	0.06	0.21	2.81	0.18	0.06	0.19	2.81	0.28	0.10	0.12
3.8E+09	2.78	0.14	0.05	0.23	2.83	0.16	0.06	0.20	2.82	0.29	0.10	0.11
3.88E+09	2.77	0.16	0.06	0.21	2.81	0.17	0.06	0.20	2.81	0.31	0.11	0.11
3.92E+09	2.74	0.17	0.06	0.19	2.78	0.19	0.07	0.17	2.79	0.31	0.11	0.11
4E+09	2.74	0.15	0.05	0.22	2.79	0.17	0.06	0.19	2.80	0.29	0.11	0.11

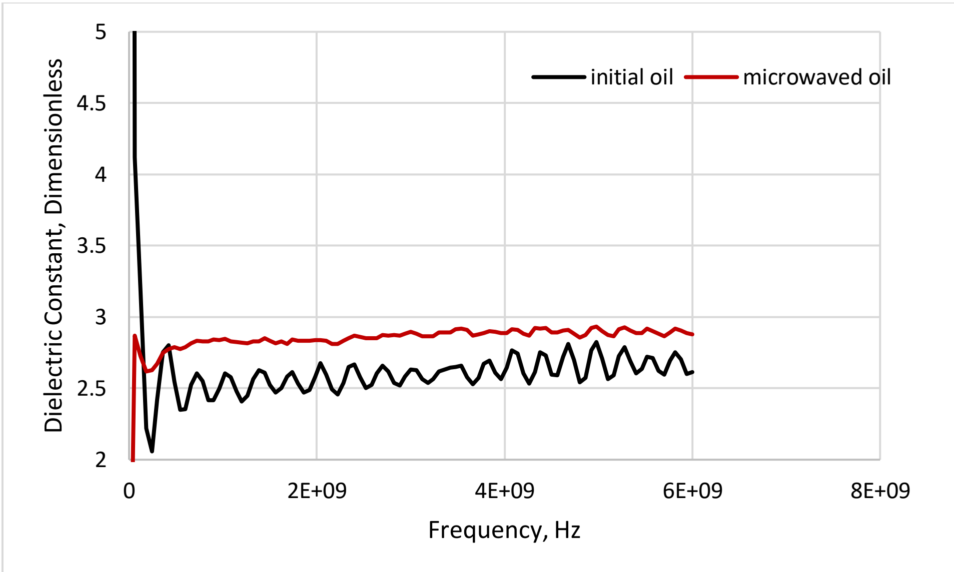


Figure A-1— Dielectric constant of C1 bulk crude + 10% nC5

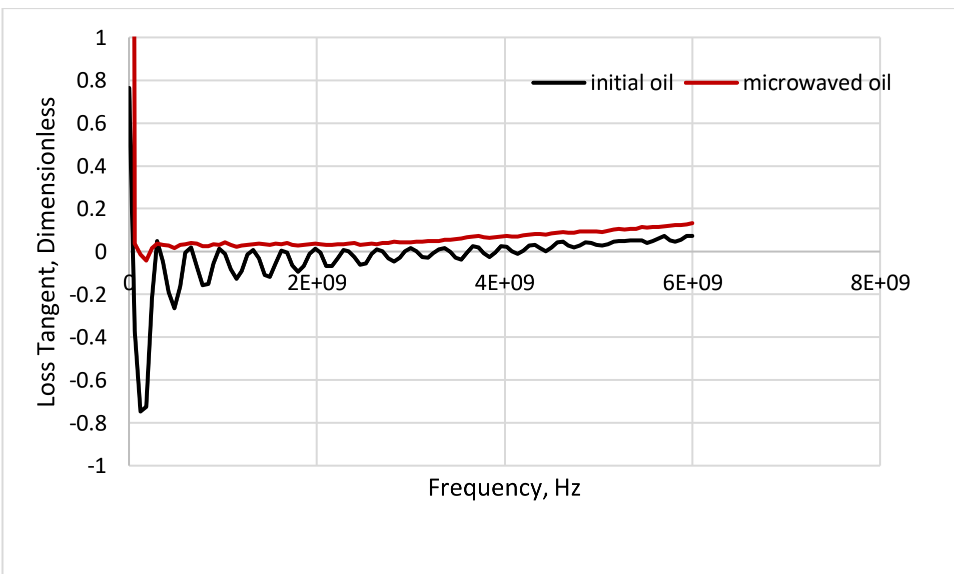


Figure A-2— Loss Tangent of C1 bulk crude + 10% nC5

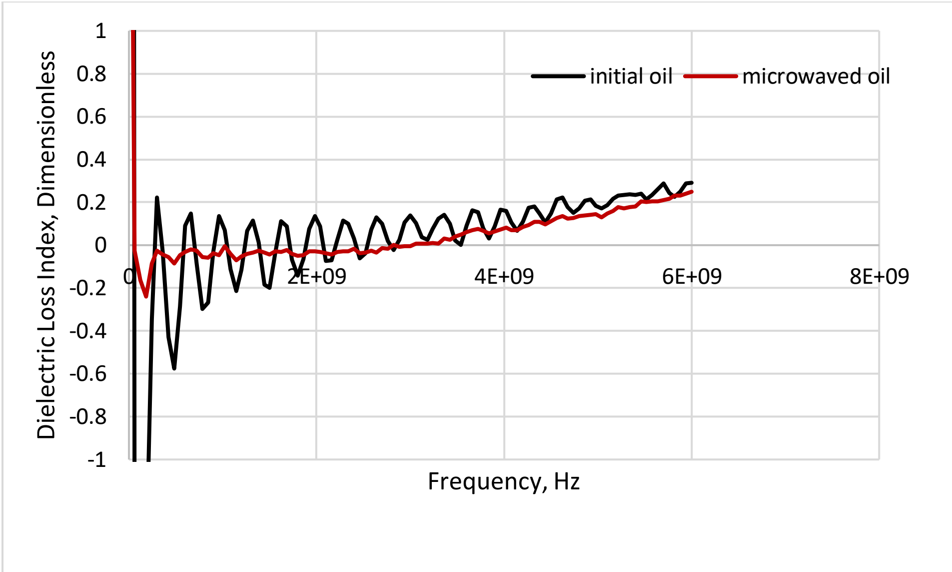


Figure A-3— Dielectric Loss Index of C1 bulk crude + 10% nC5

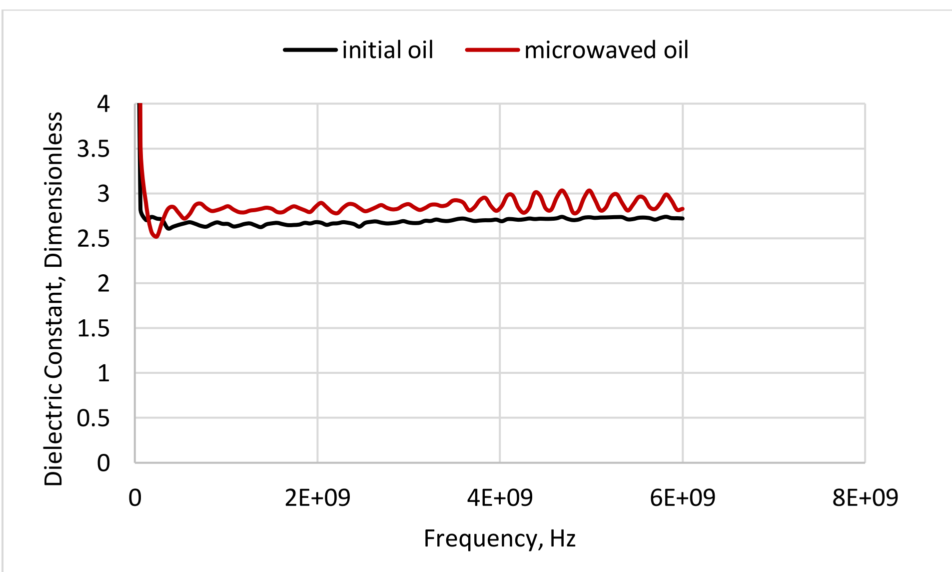


Figure A-4— Dielectric Constant of C1 bulk crude + 20% nC5

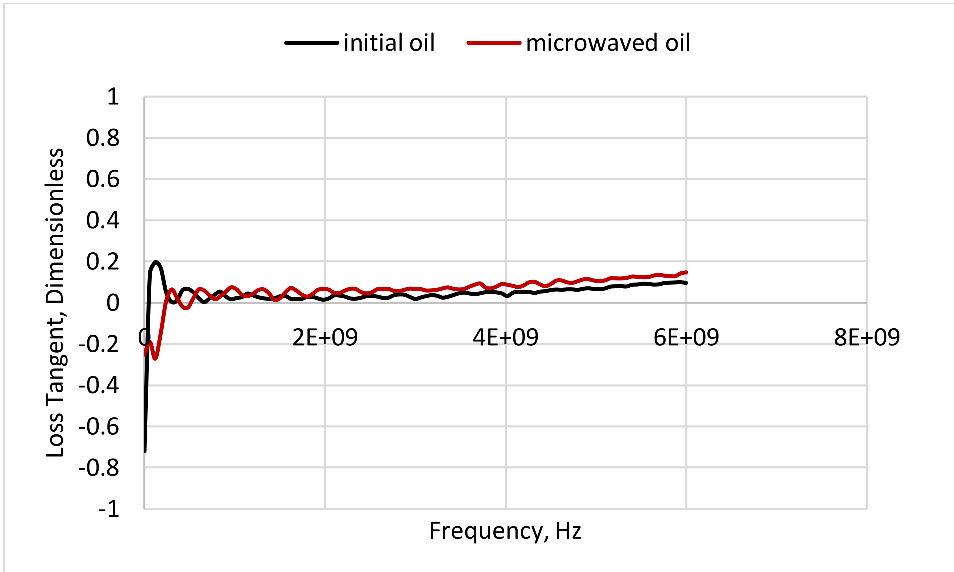


Figure A-5— Loss Tangent of C1 bulk crude + 20% nC5

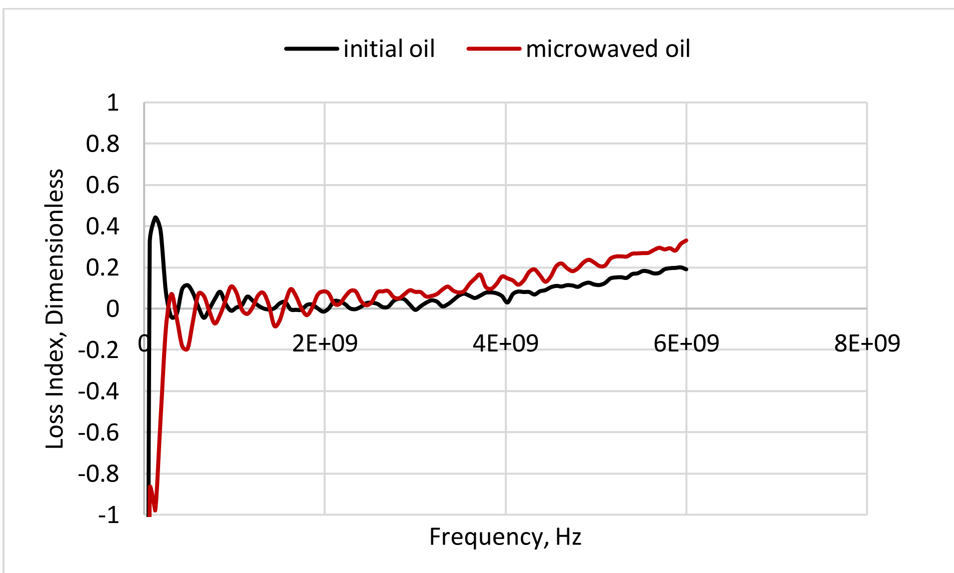


Figure A-6— Loss Index of C1 bulk crude + 20% nC5

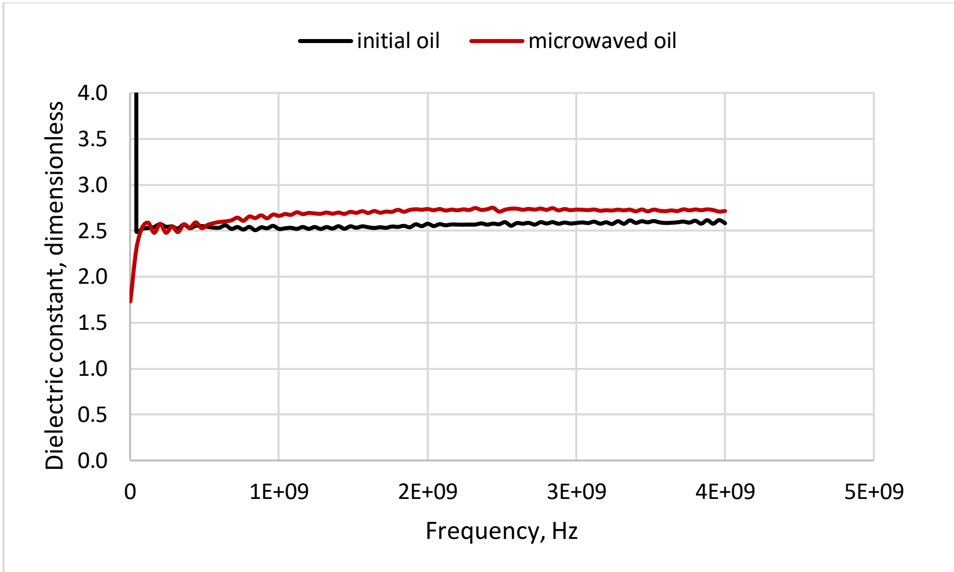


Figure A-7— Dielectric Constant of C1 bulk crude + 50% nC5

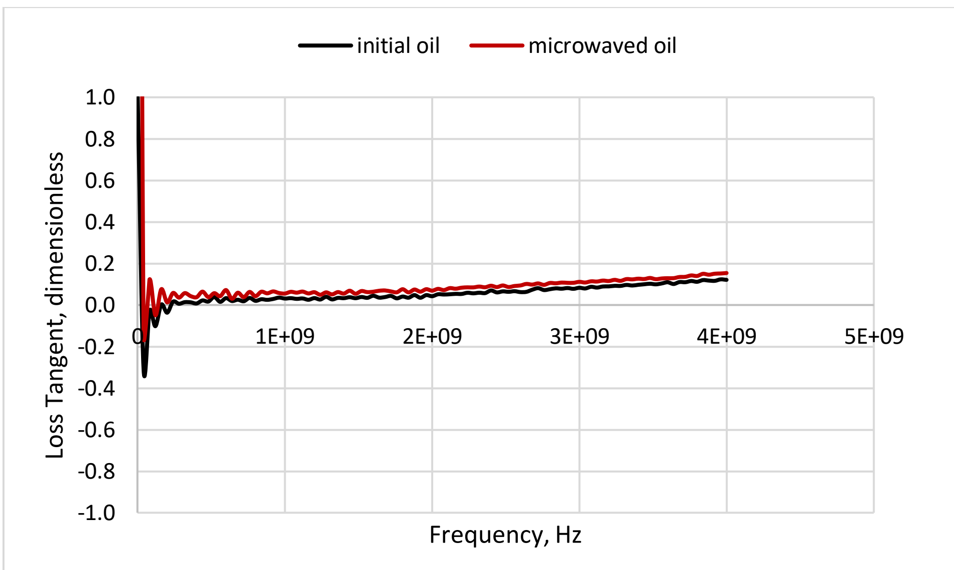


Figure A-8— Loss Tangent of C1 bulk crude + 50% nC5

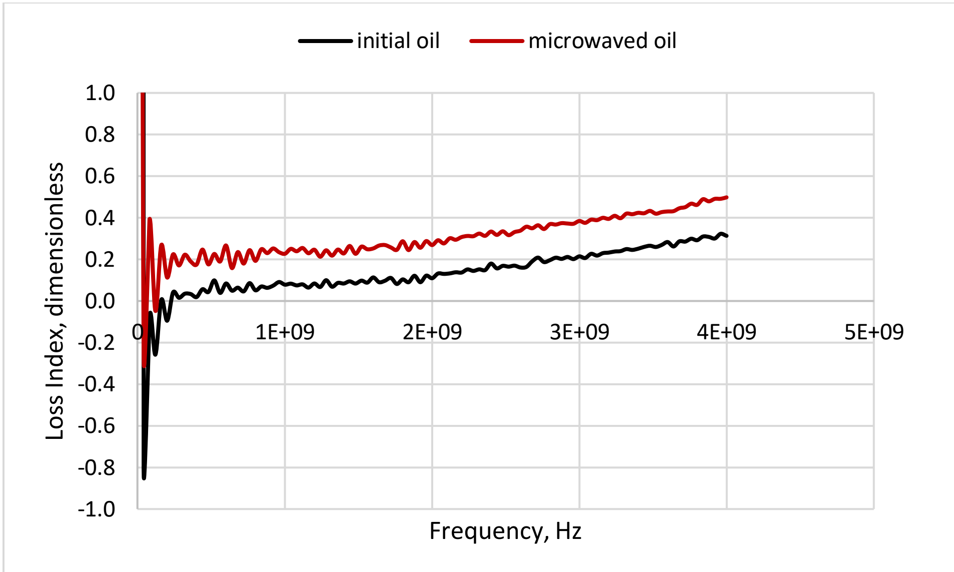


Figure A-9— Loss Index of C1 bulk crude + 50% nC5

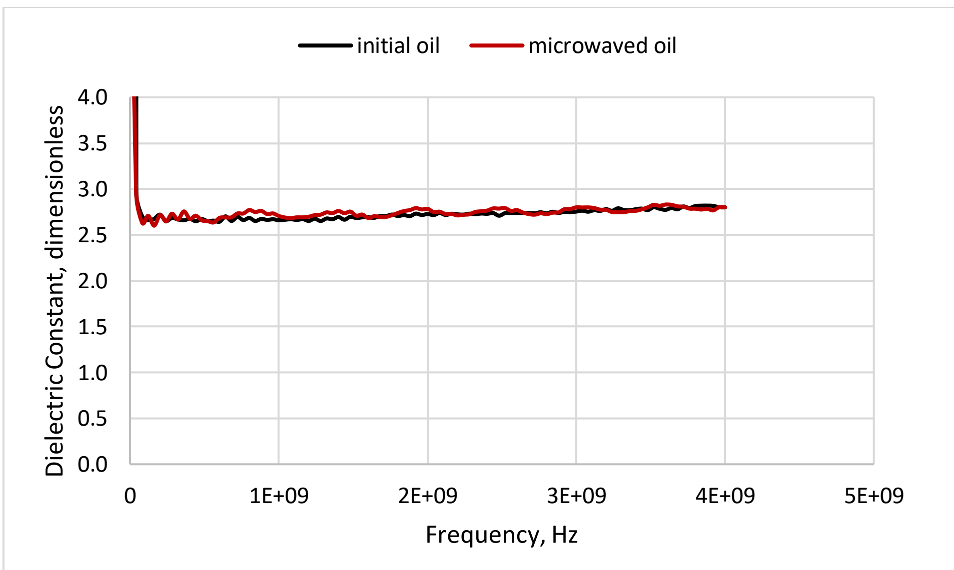


Figure A-10— Dielectric constant of C1 bulk crude + 10% nC7

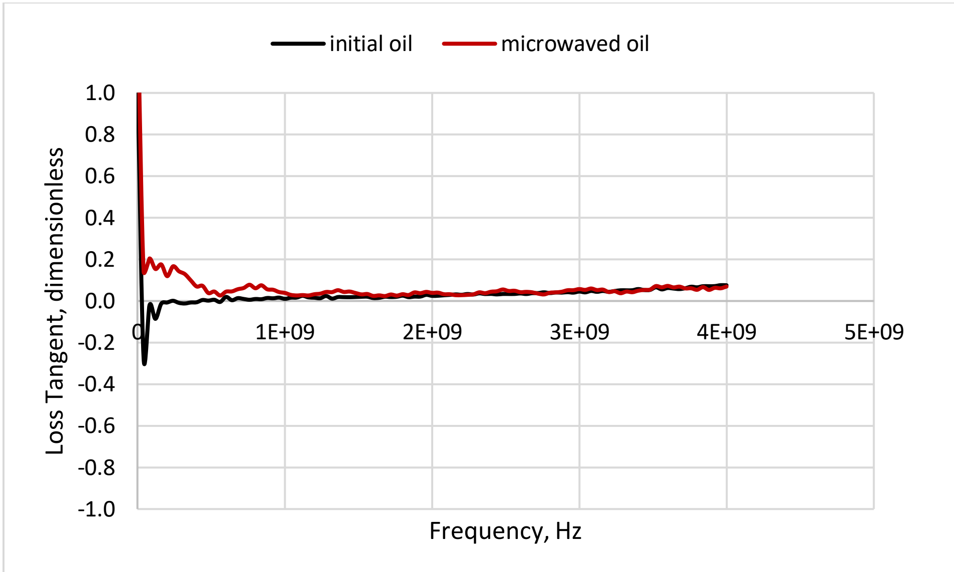


Figure A-11— Loss Tangent of C1 bulk crude + 10% nC7

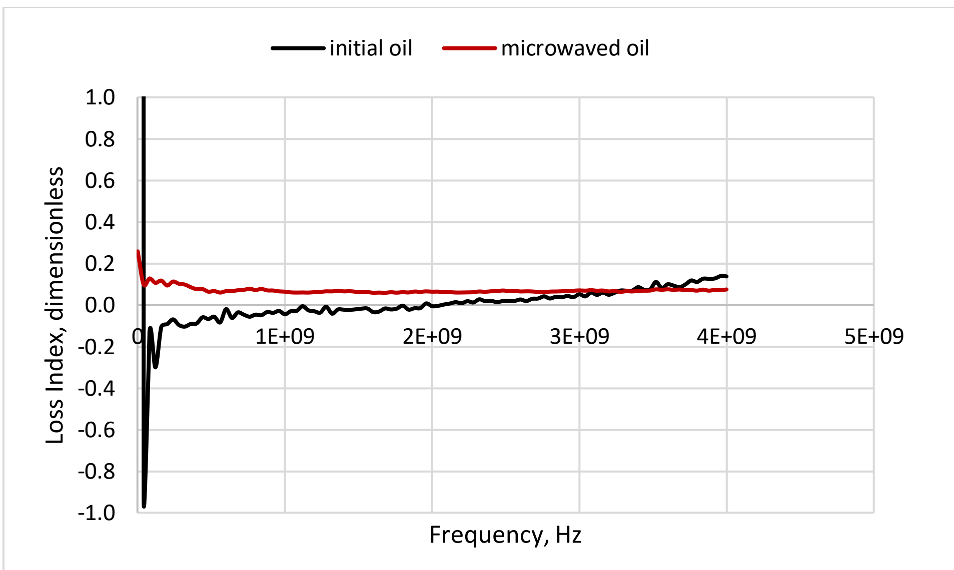


Figure A-12— Loss Index of C1 bulk crude + 10% nC7

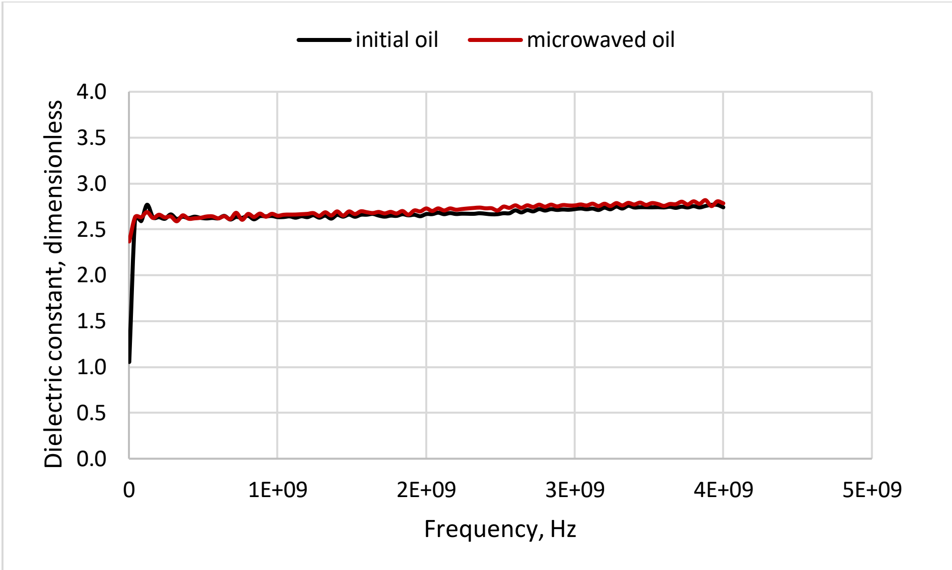


Figure A-13— Dielectric constant of C1 bulk crude + 20% nC7

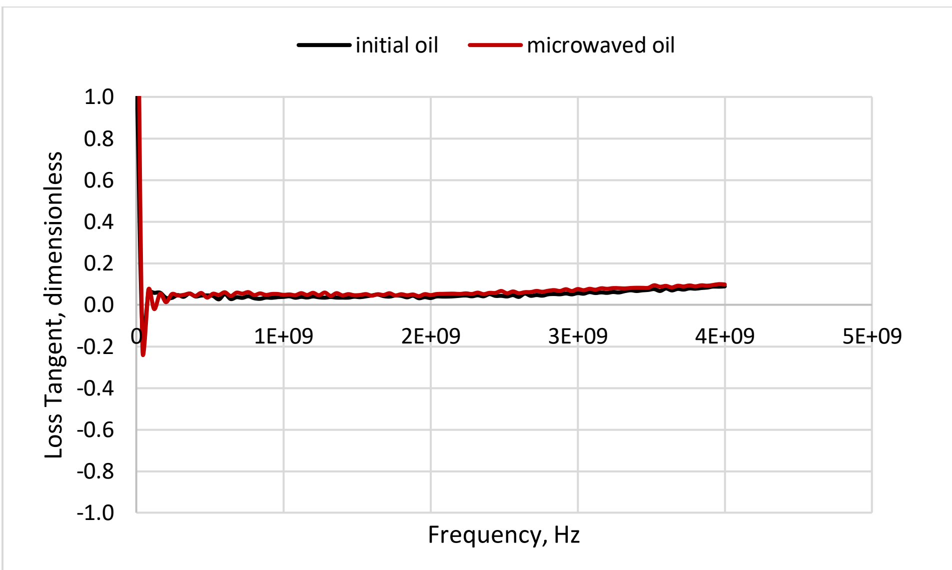


Figure A-14— Loss Tangent of C1 bulk crude + 20% nC7

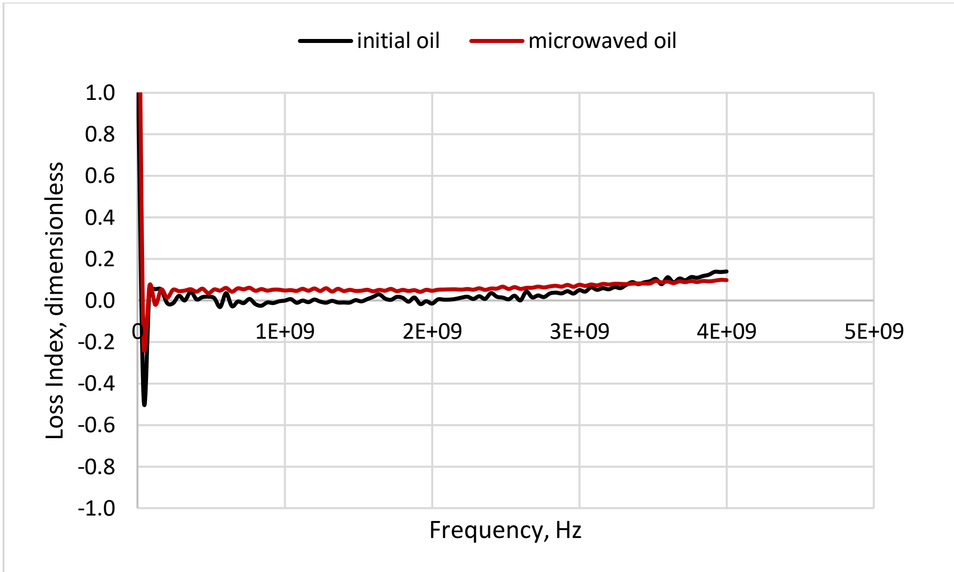


Figure A-15— Loss Index of C1 bulk crude + 20% nC7

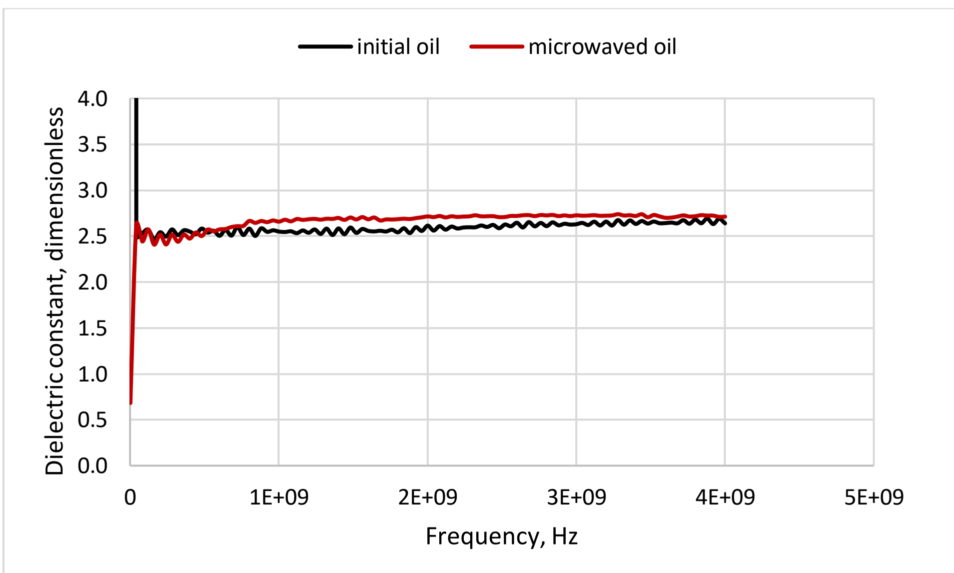


Figure A-16— Dielectric constant of C1 bulk crude + 50% nC7

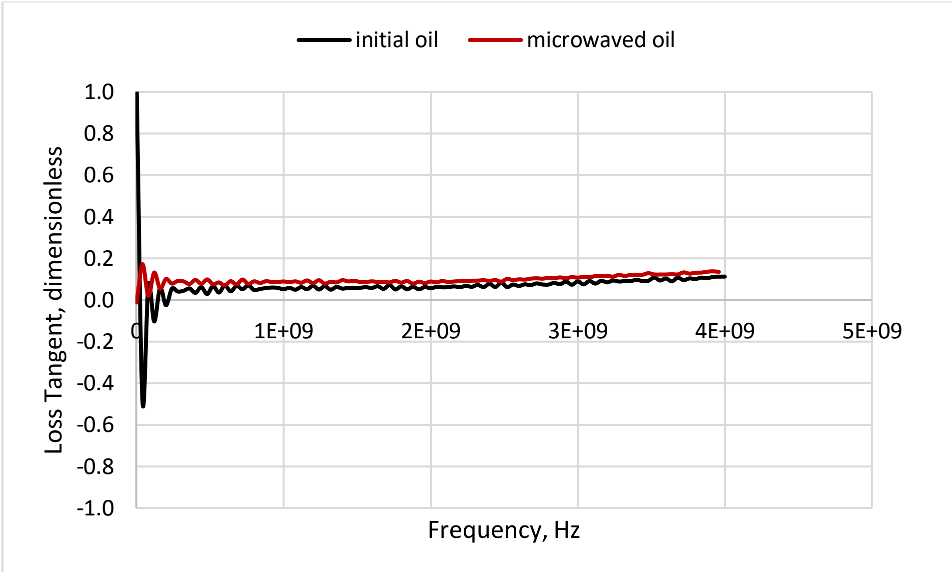


Figure A-17— Loss Tangent of C1 bulk crude + 50% nC7

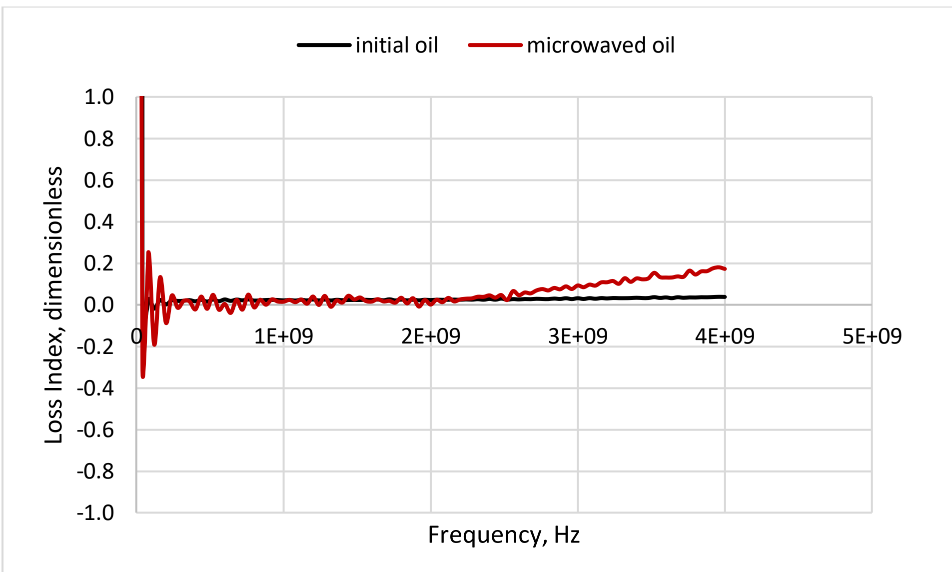


Figure A-18— Loss Index of C1 bulk crude + 50% nC7

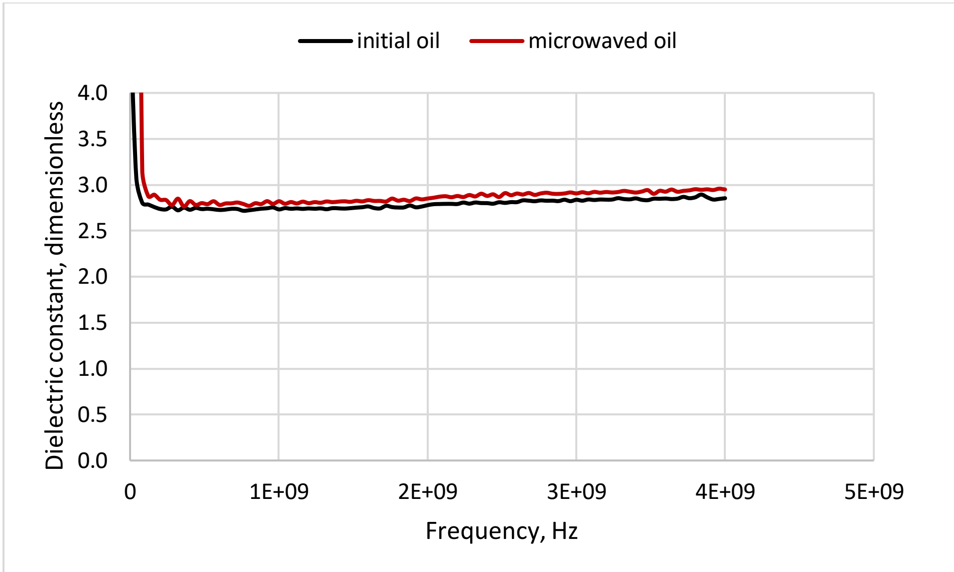


Figure A-19— Dielectric Constant of C1 bulk crude + 10% Toluene

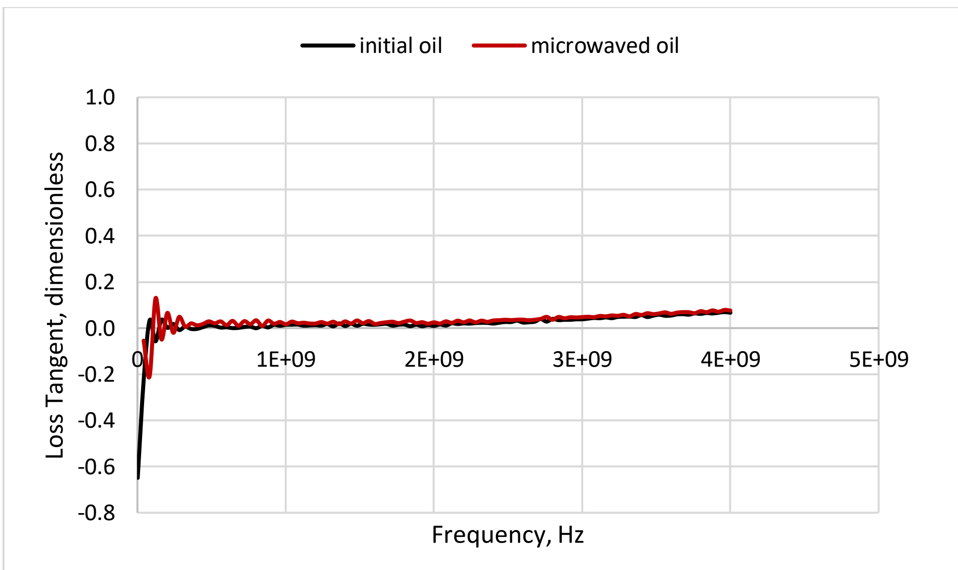


Figure A-20— Loss Tangent of C1 bulk crude + 10% Toluene

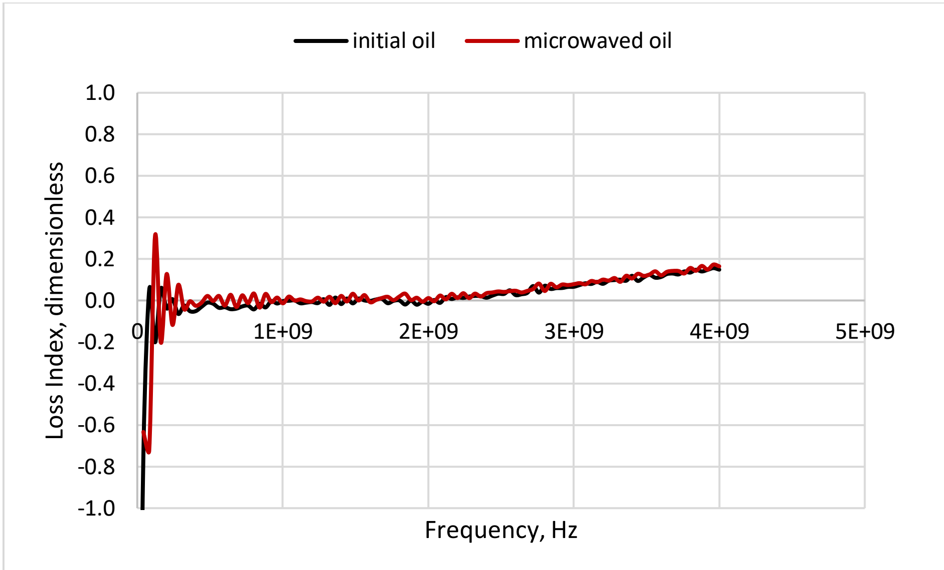


Figure A-21— Loss Index of C1 bulk crude + 10% Toluene

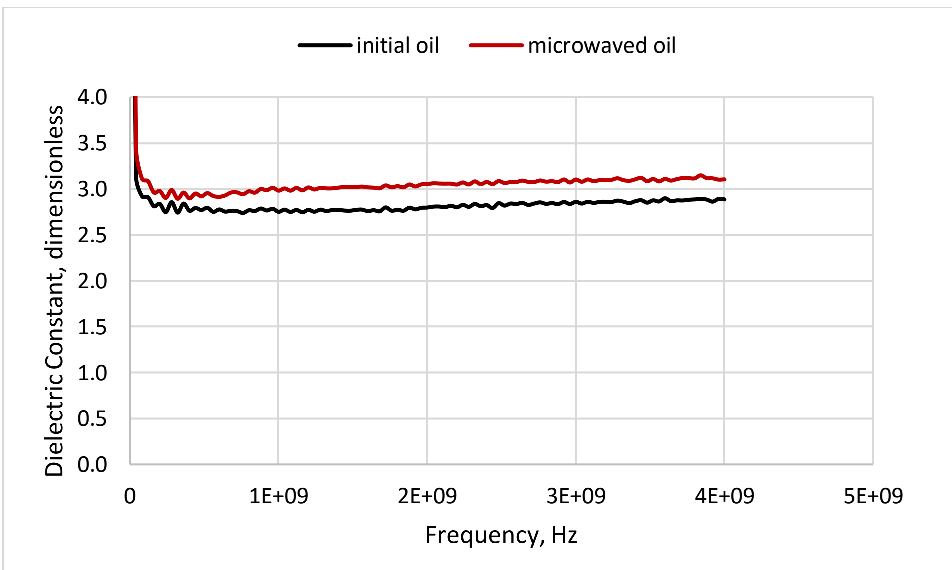


Figure A-22— Dielectric Constant of C1 bulk crude + 20% Toluene

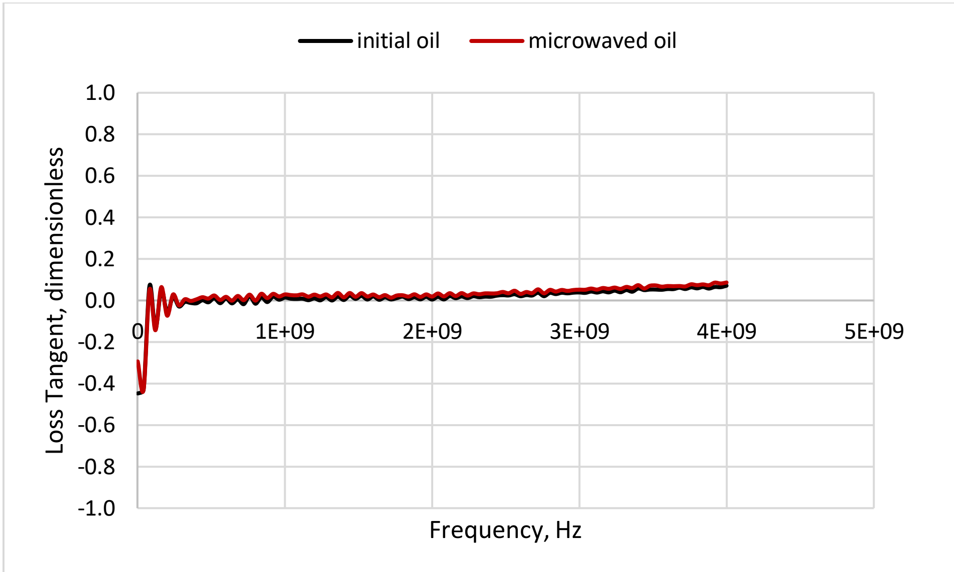


Figure A-23— Loss Tangent of C1 bulk crude + 20% Toluene

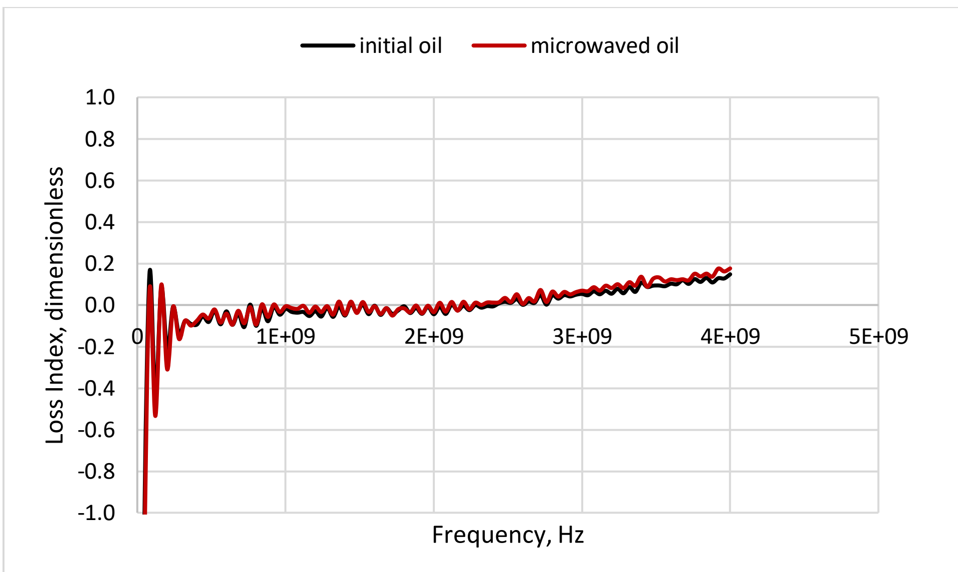


Figure A-24— Loss Index of C1 bulk crude + 20% Toluene

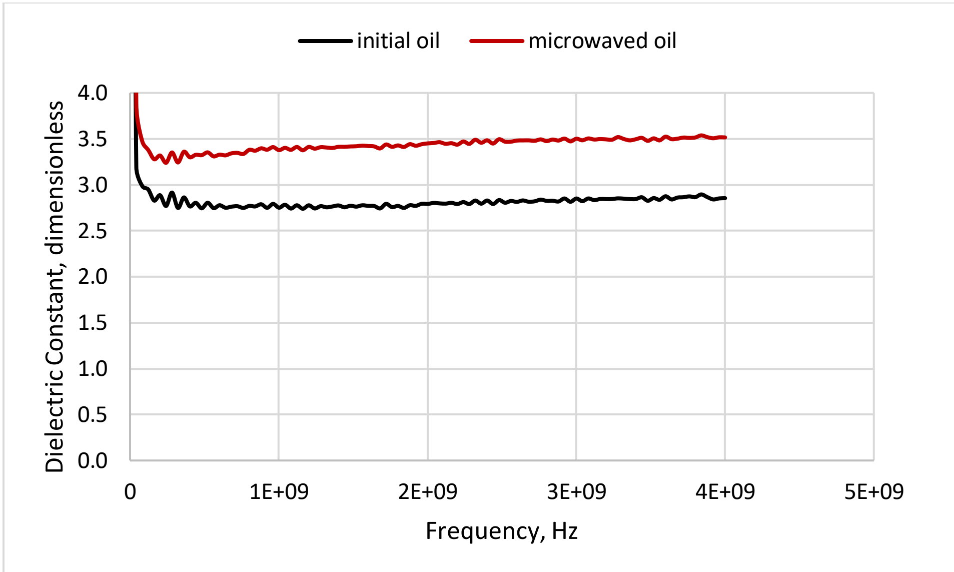


Figure A-25— Dielectric Constant of C1 bulk crude + 50% Toluene

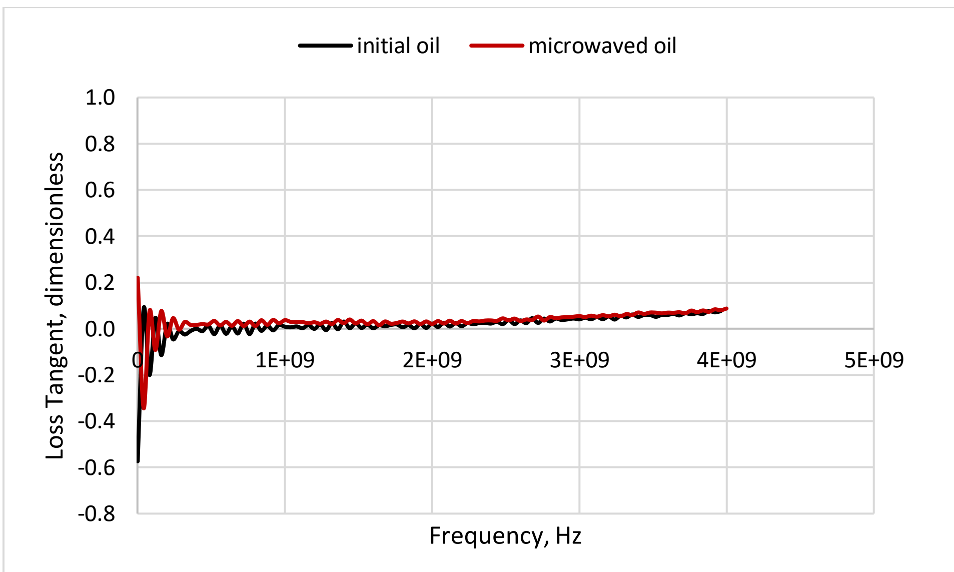


Figure A-26— Loss Tangent of C1 bulk crude + 50% Toluene

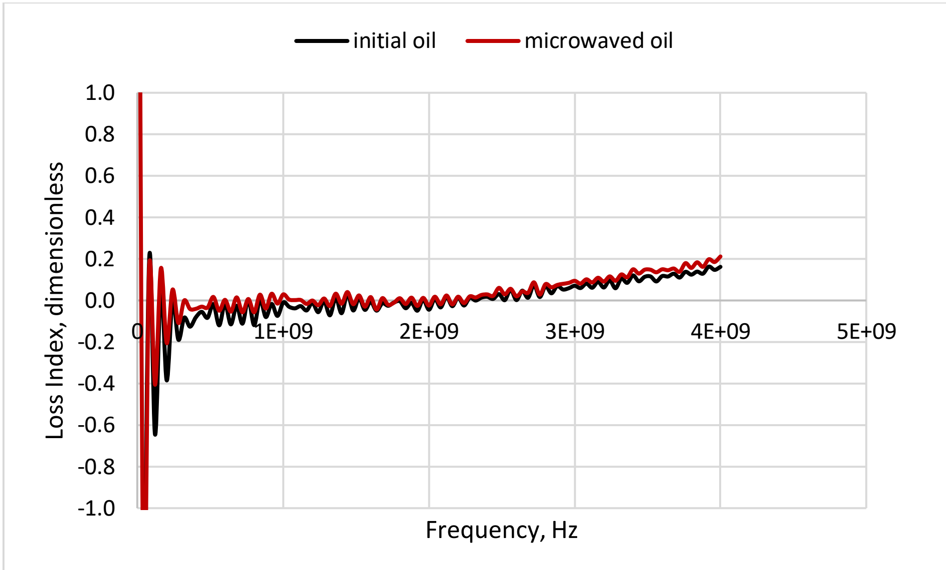


Figure A-27— Loss Index of C1 bulk crude + 50% Toluene

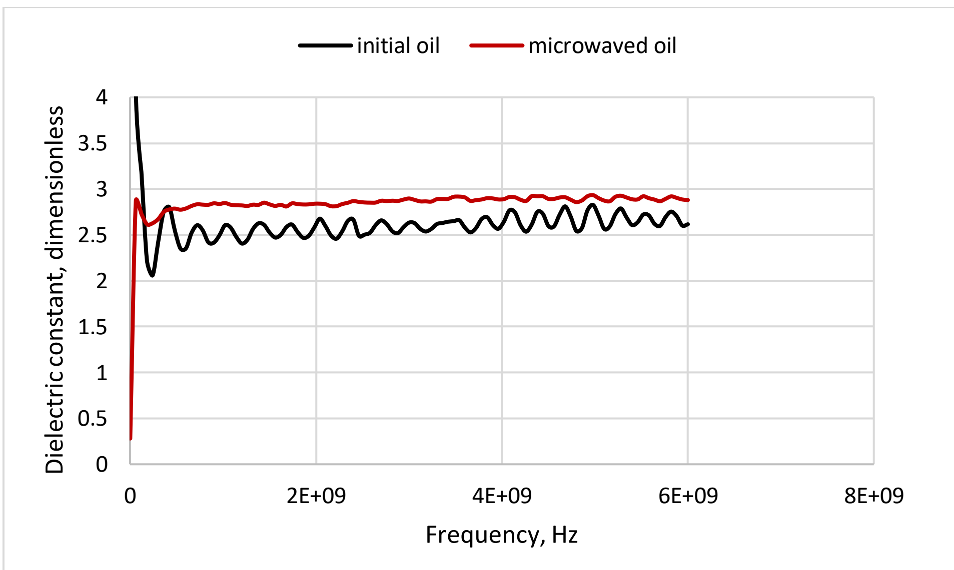


Figure A-28— Dielectric constant of C2 bulk crude + 10% nC5

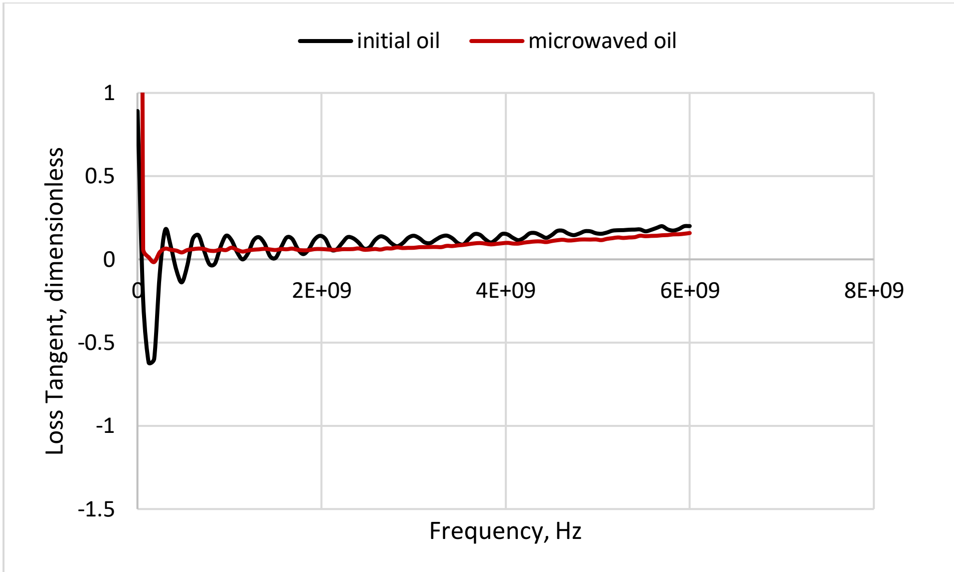


Figure A-29— Loss Tangent of C2 bulk crude + 10% nC5

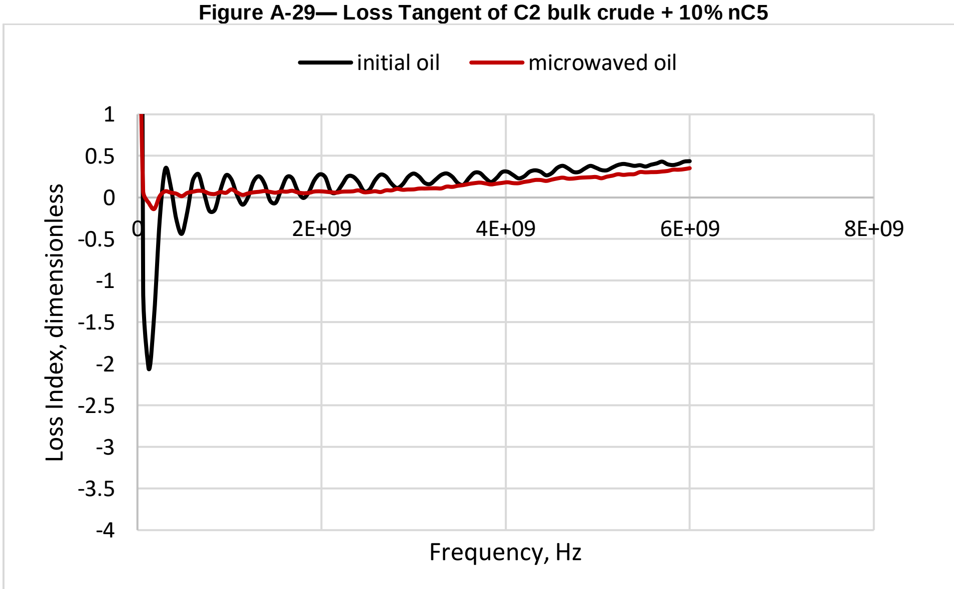


Figure A-30— Loss Index of C2 bulk crude + 10% nC5

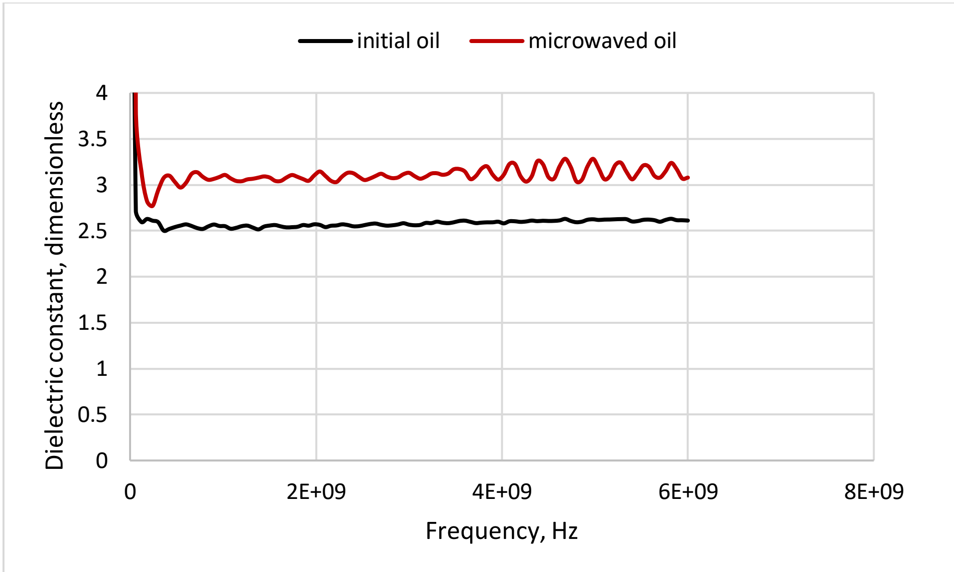


Figure A-31— Dielectric Constant of C2 bulk crude + 20% nC5

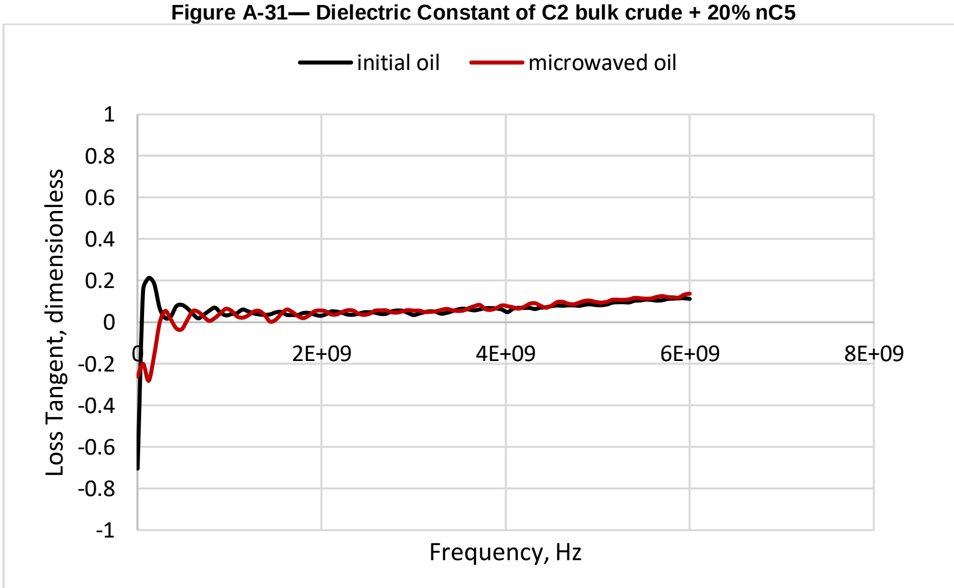


Figure A-32— Loss Tangent of C2 bulk crude + 20% nC5

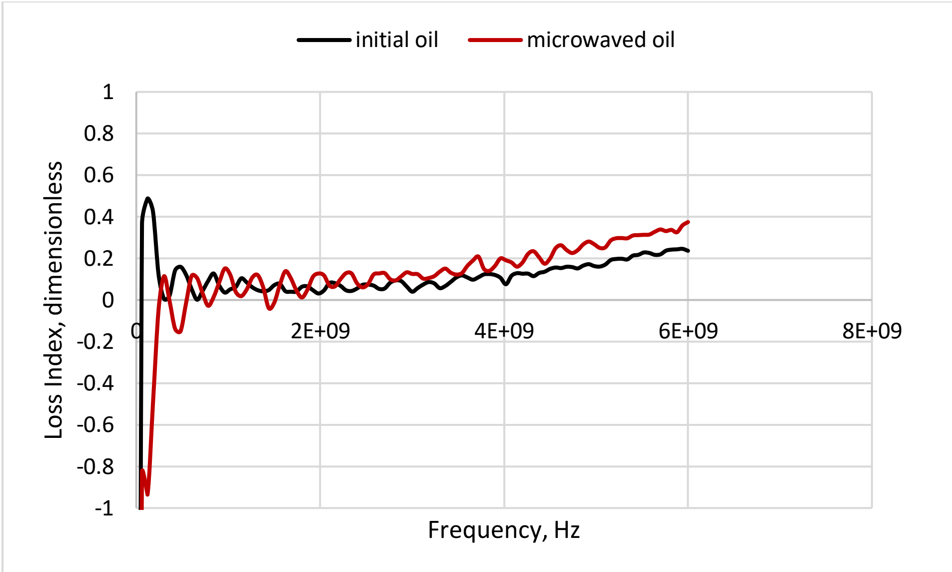


Figure A-33— Loss Index of C2 bulk crude + 20% nC5

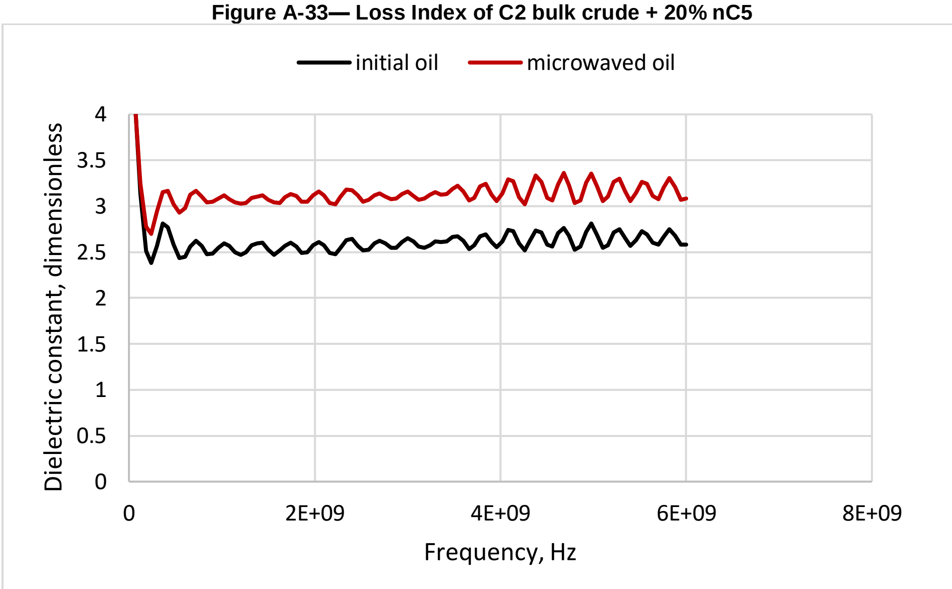


Figure A-34— Dielectric constant of C2 bulk crude + 50% nC5

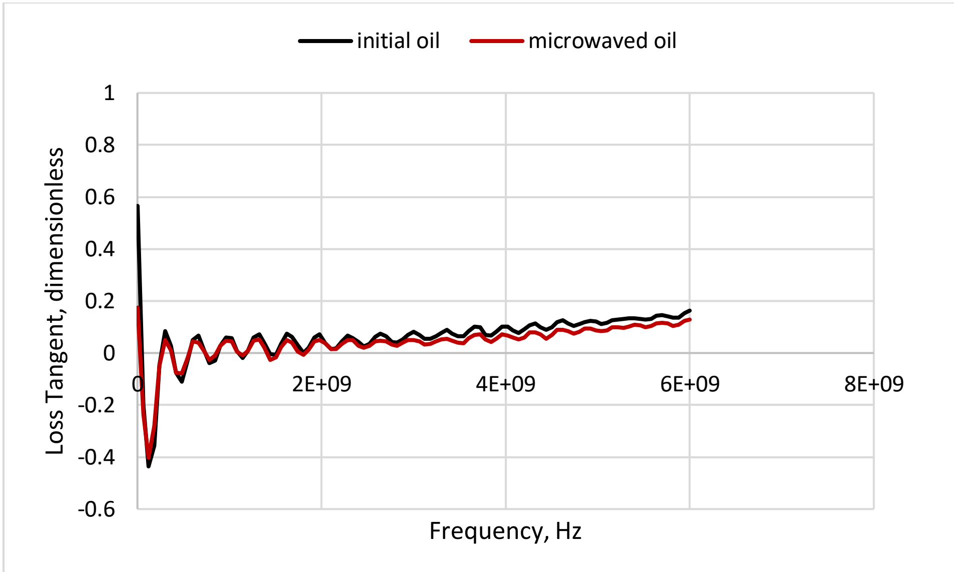


Figure A-35— Loss Tangent of C2 bulk crude + 50% nC5

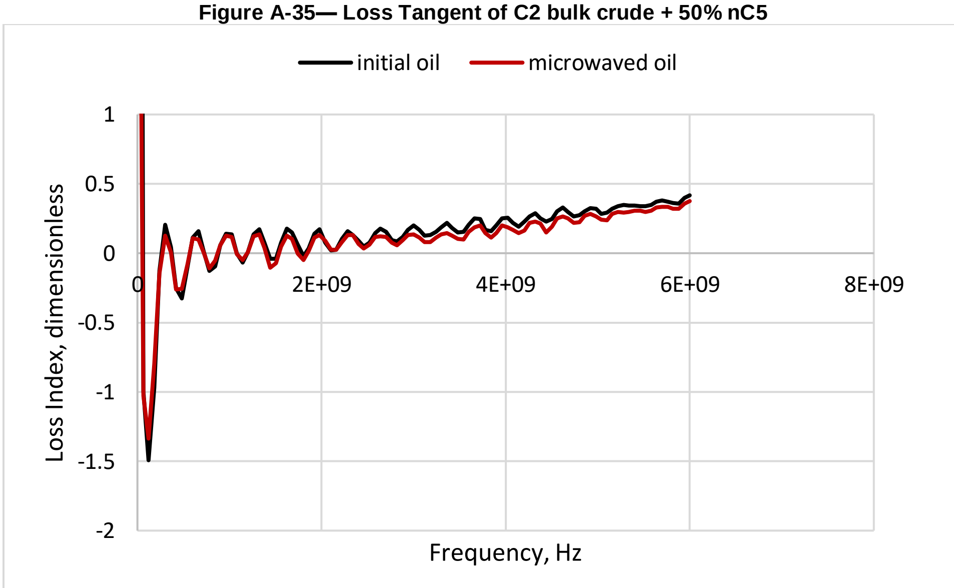


Figure A-36— Loss Index of C2 bulk crude + 50% nC5

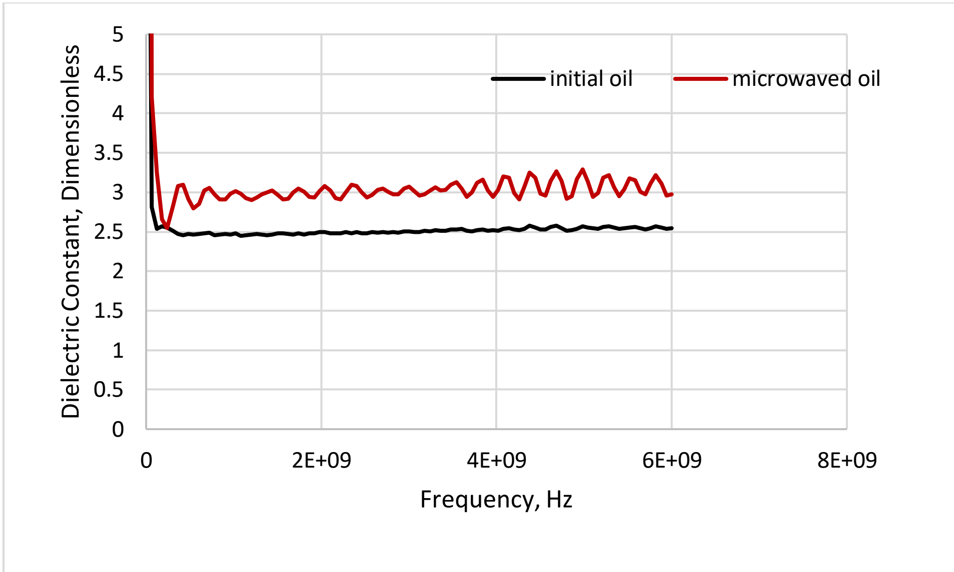


Figure A-37— Dielectric Constant of C2 bulk crude + 10% nC7

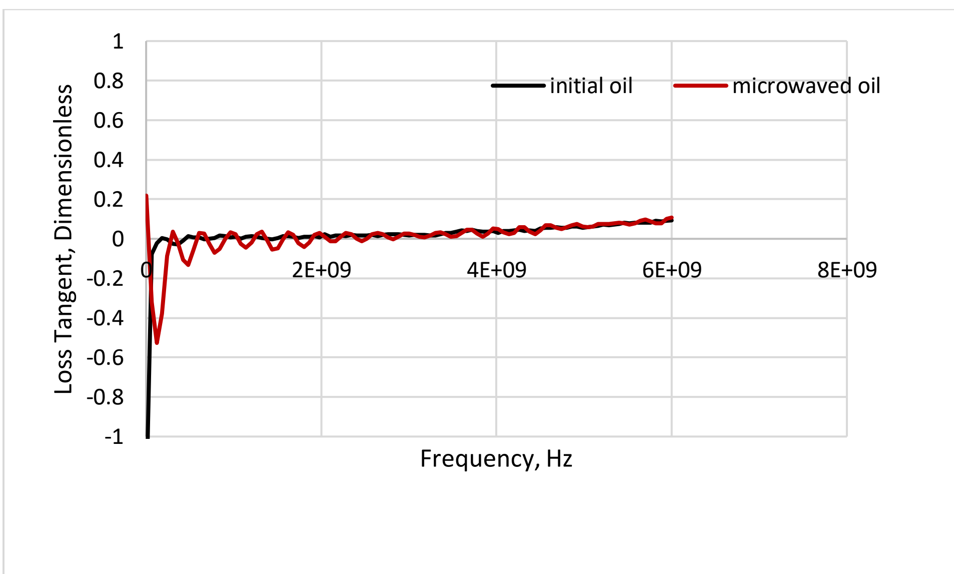


Figure A-38— Loss Tangent of C2 bulk crude + 10% nC7

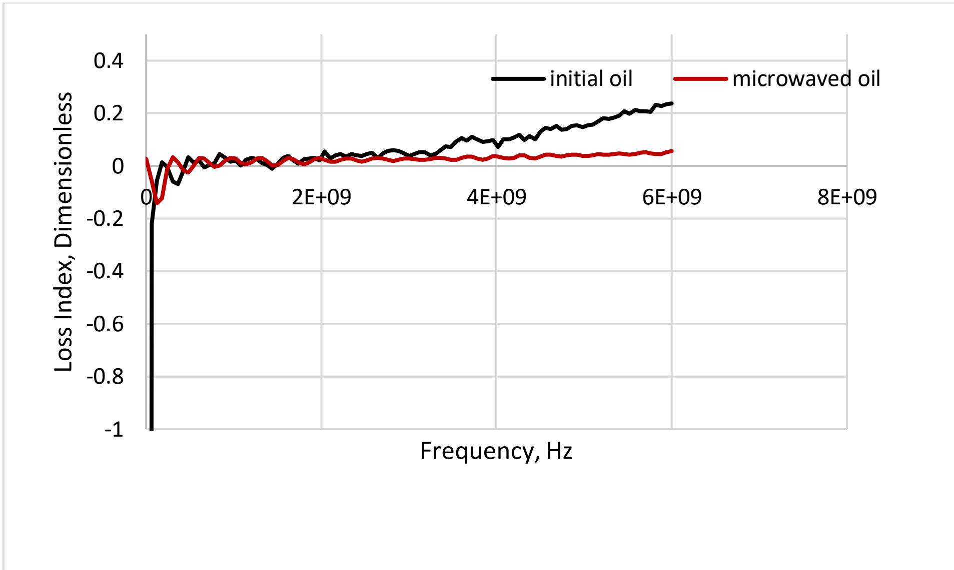


Figure A-39— Loss Index of C2 bulk crude + 10% nC7

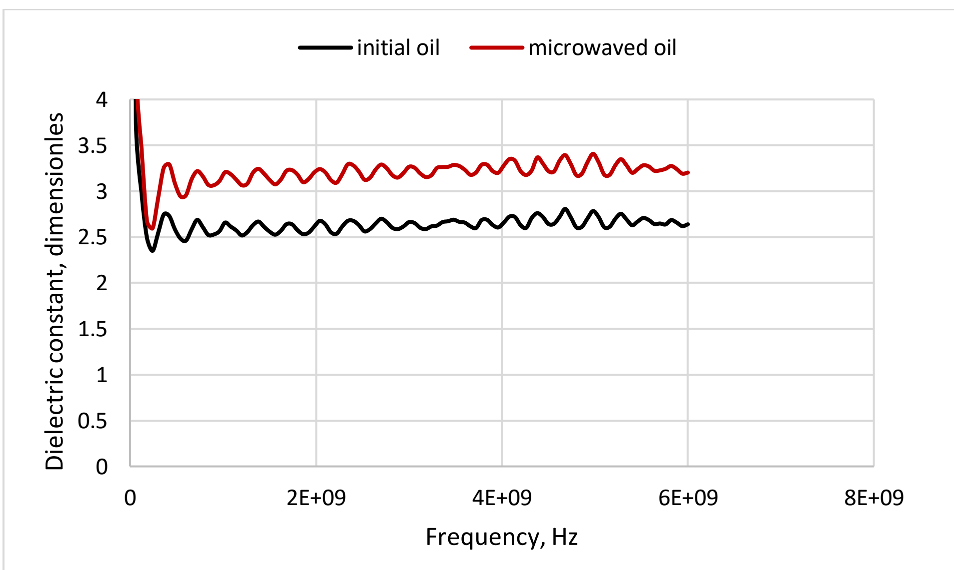


Figure A-40— Dielectric constant of C2 bulk crude + 20% nC7

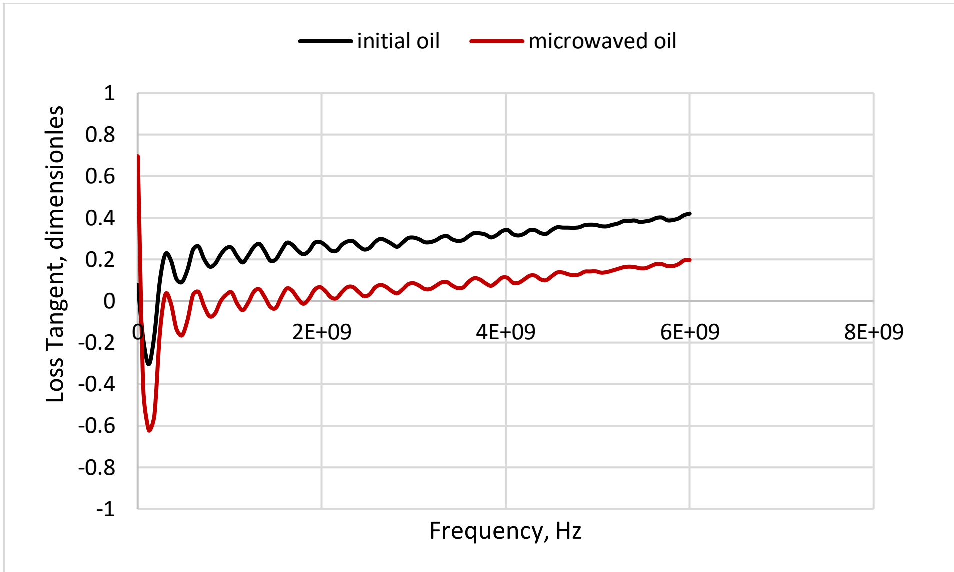


Figure A-41— Loss Tangent of C2 bulk crude + 20% nC7

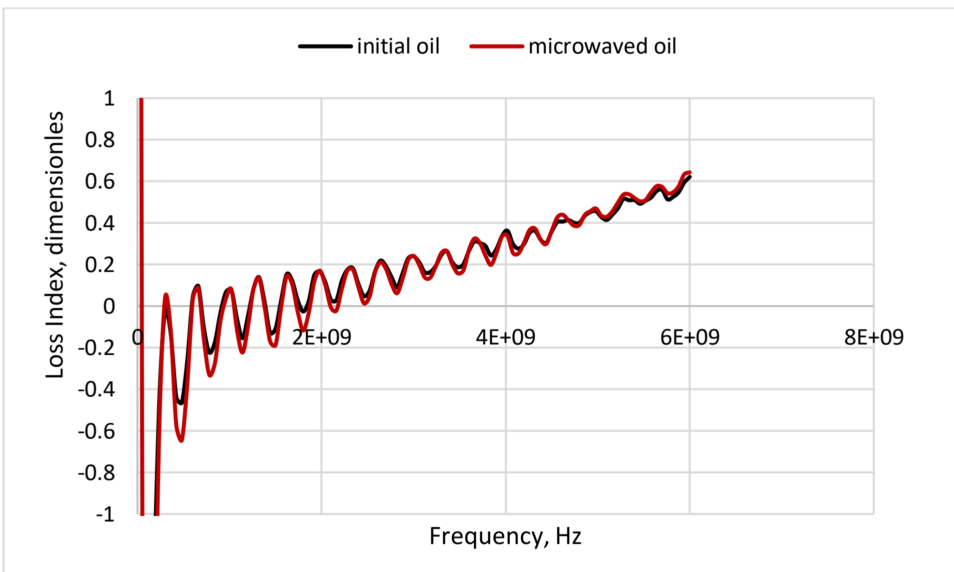


Figure A-42— Loss Index of C2 bulk crude + 20% nC7

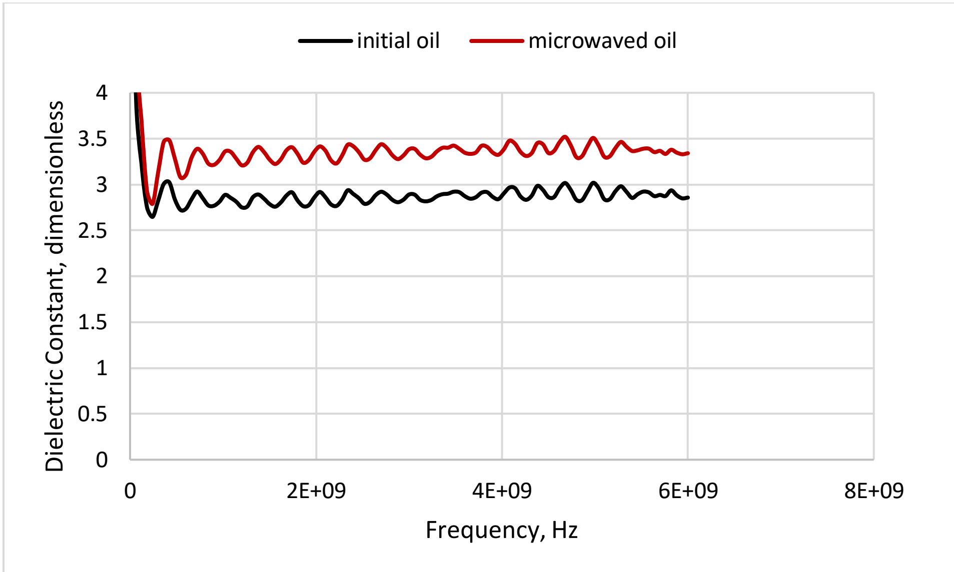


Figure A-43— Dielectric Constant of C2 bulk crude + 50% nC7

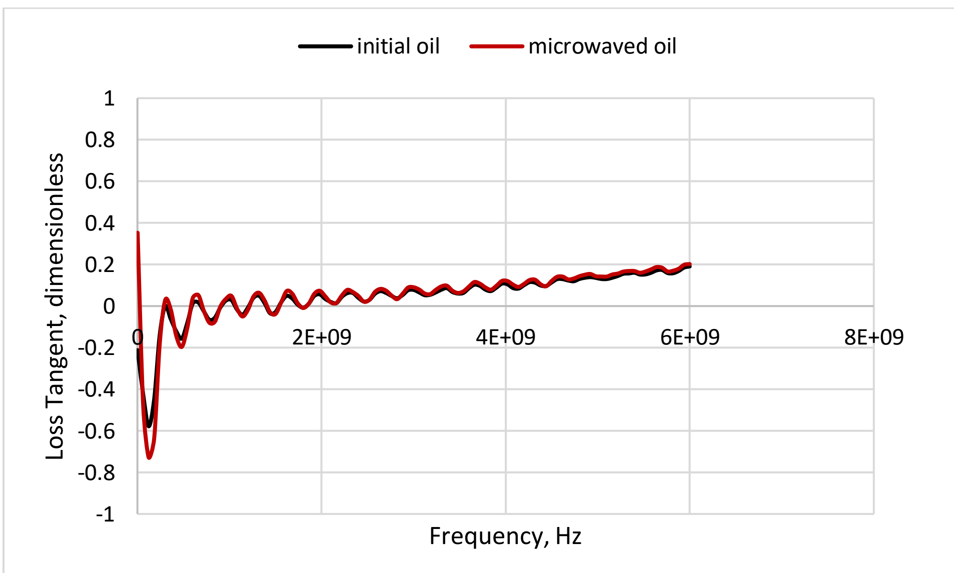


Figure A-44— Loss Tangent of C2 bulk crude + 50% nC7

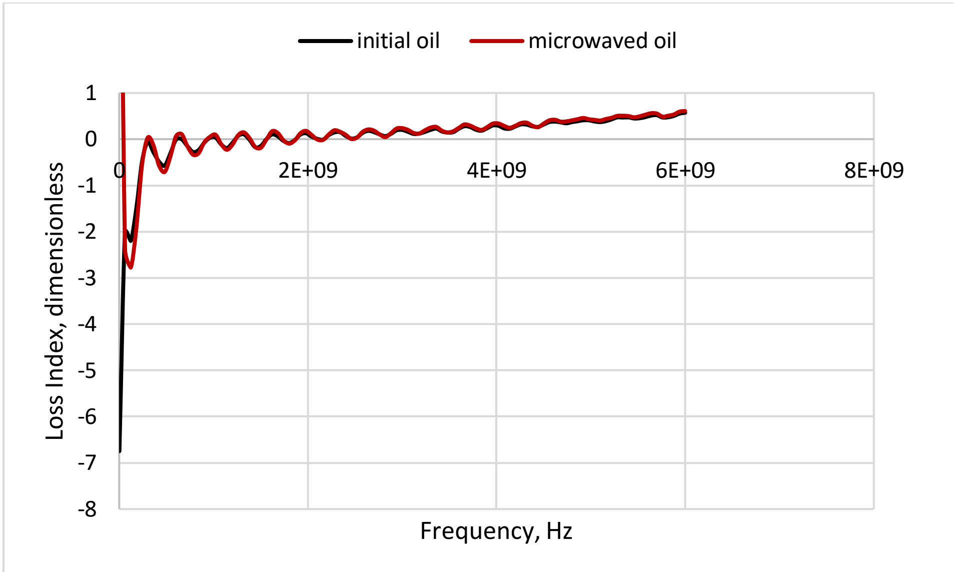


Figure A-45— Loss Index of C2 bulk crude + 50% nC7

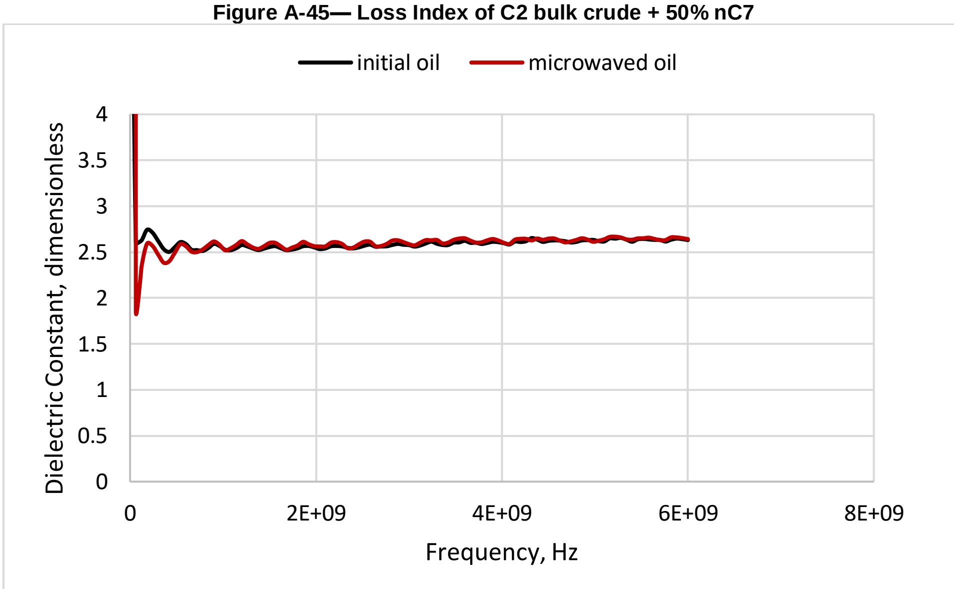


Figure A-46— Dielectric constant of C2 bulk crude + 10% toluene

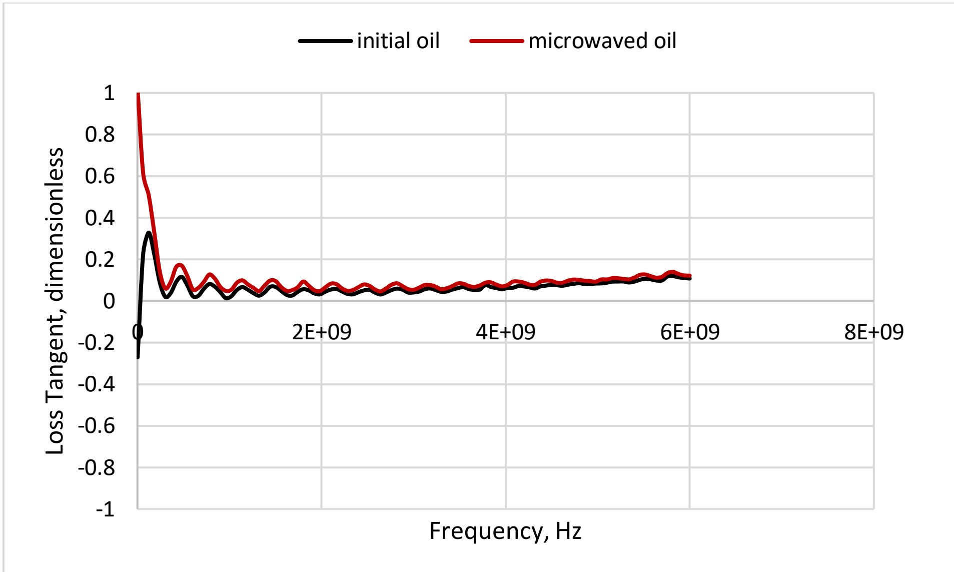


Figure A-47— Loss Tangent of C2 bulk crude + 10% toluene

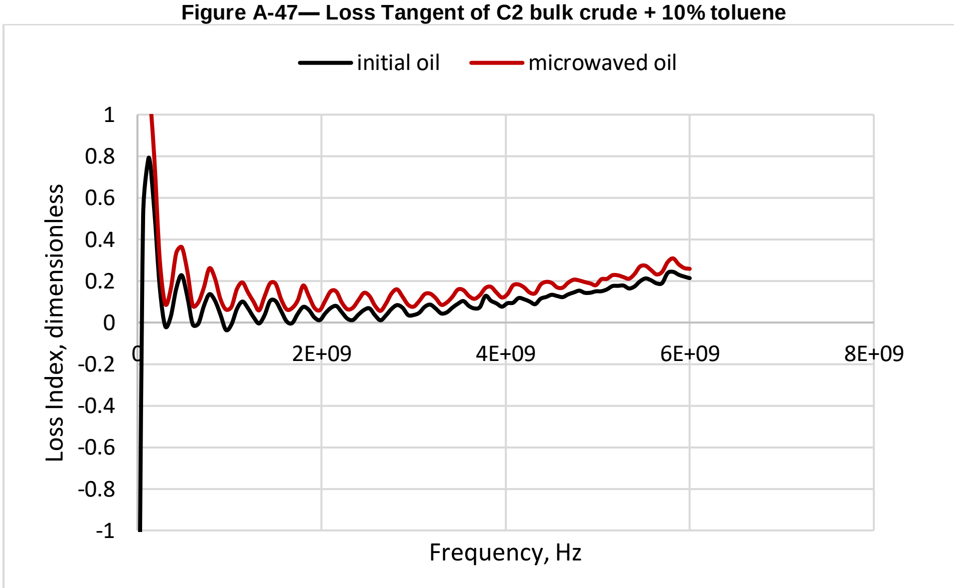


Figure A-48— Loss Index of C2 bulk crude + 10% toluene

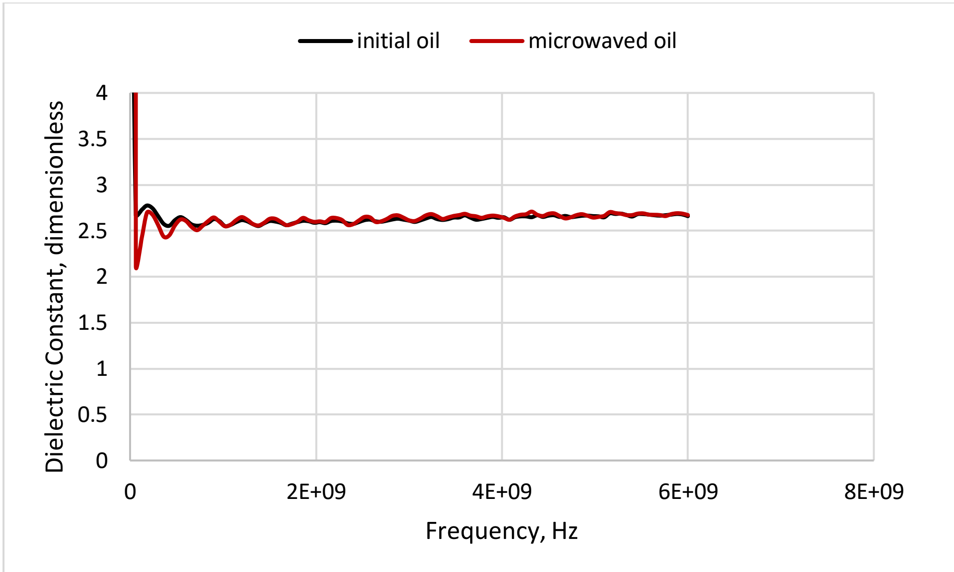


Figure A-49— Dielectric constant of C2 bulk crude + 20% toluene

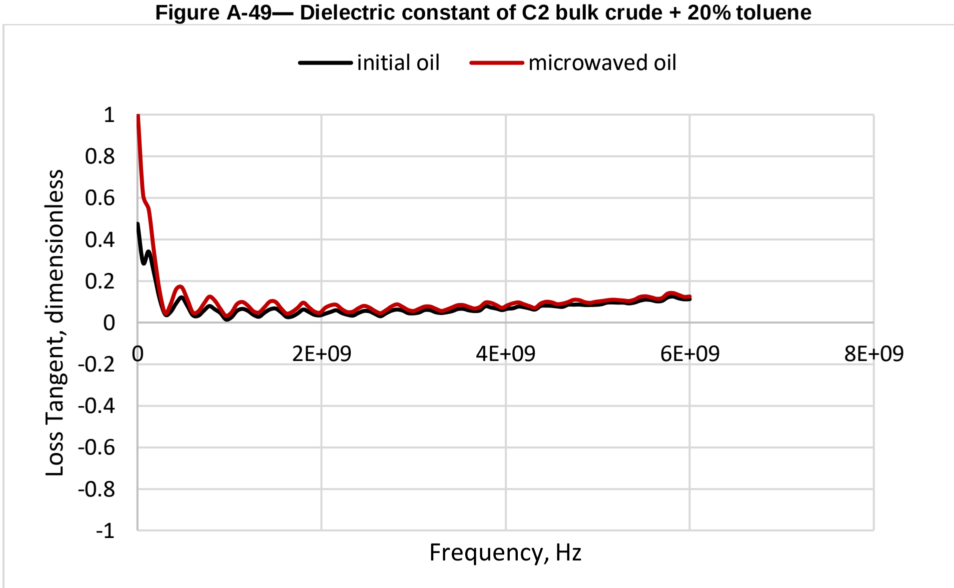


Figure A-50— Loss Tangent of C2 bulk crude + 20% toluene

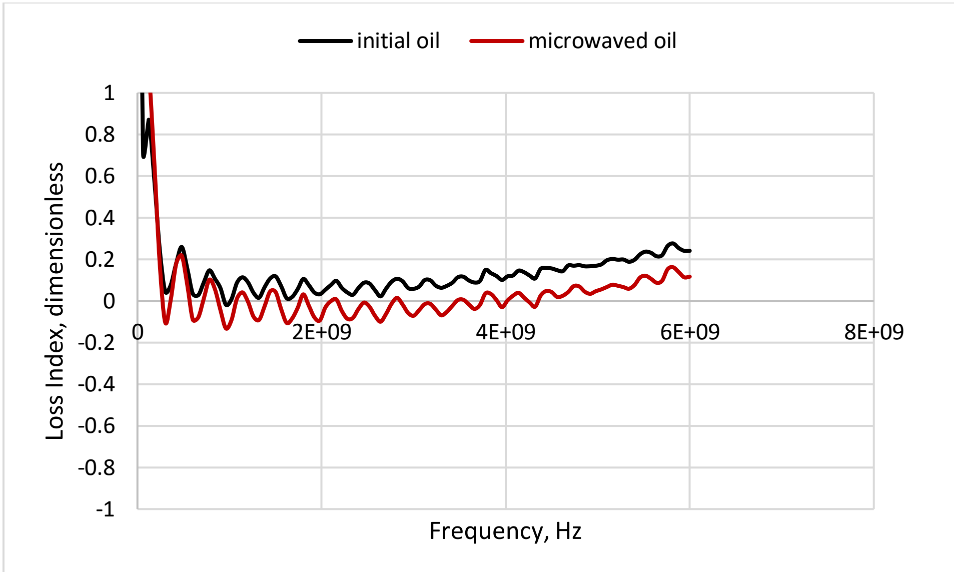


Figure A-51— Loss Index of C2 bulk crude + 20% toluene

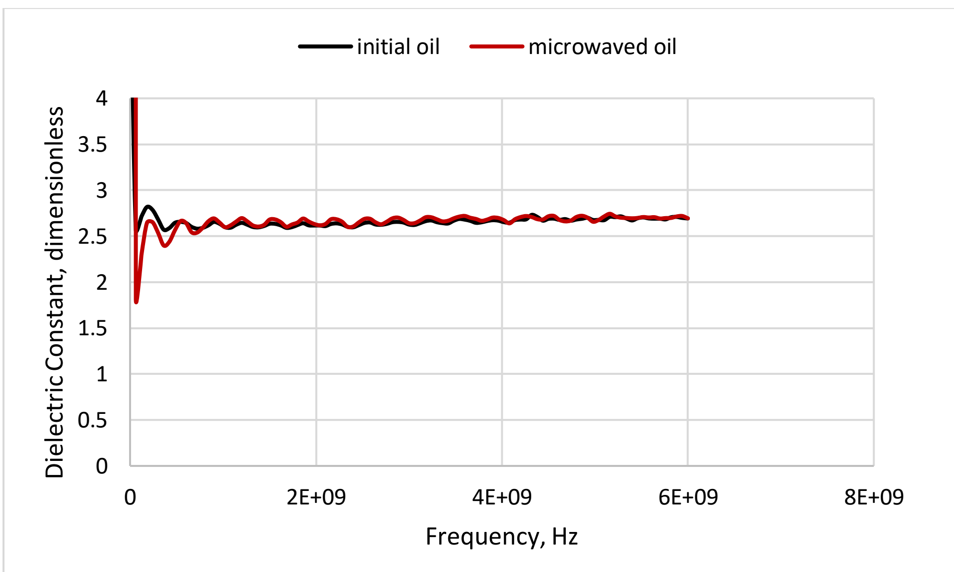


Figure A-52— Dielectric constant of C2 bulk crude + 50% toluene

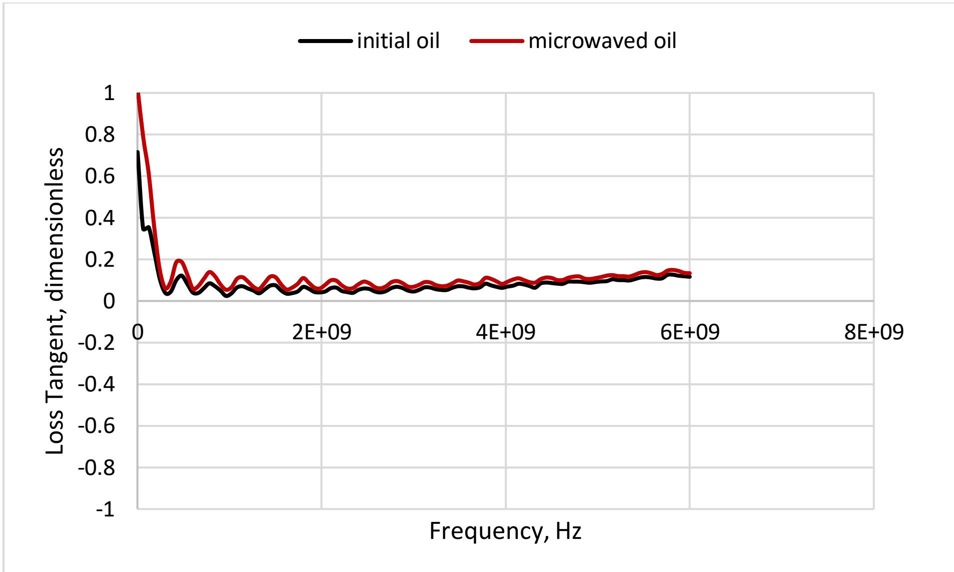


Figure A-53— Loss Tangent of C2 bulk crude + 50% toluene

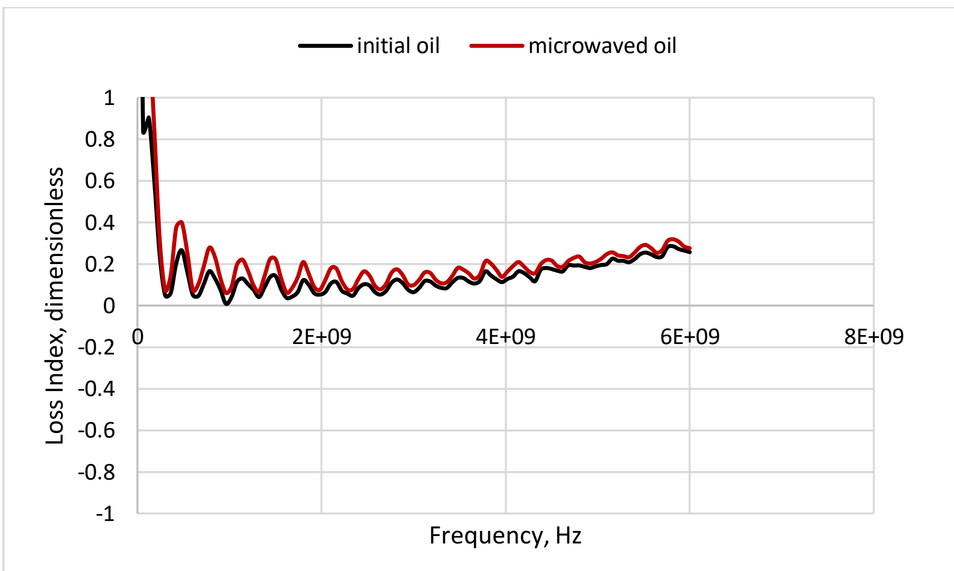


Figure A-54— Loss Index of C2 bulk crude + 50% toluene

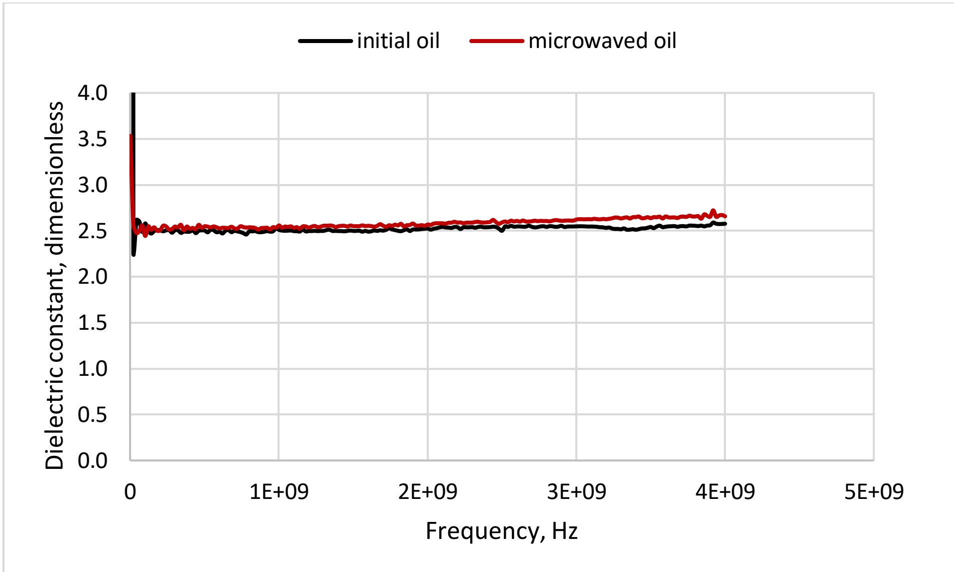


Figure A-55— Dielectric constant of C3 bulk crude + 10% nC5

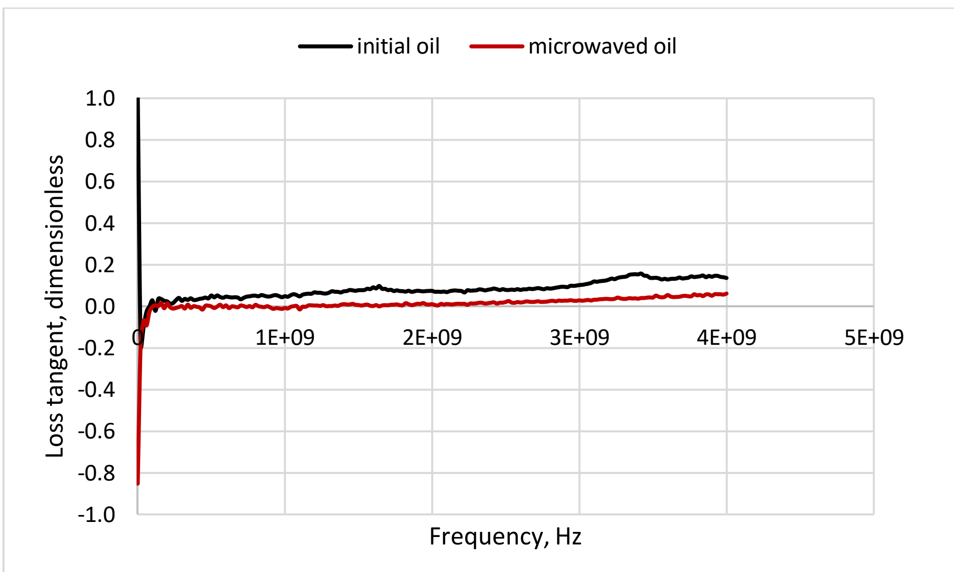


Figure A-56— Loss Tangent of C3 bulk crude + 10% nC5

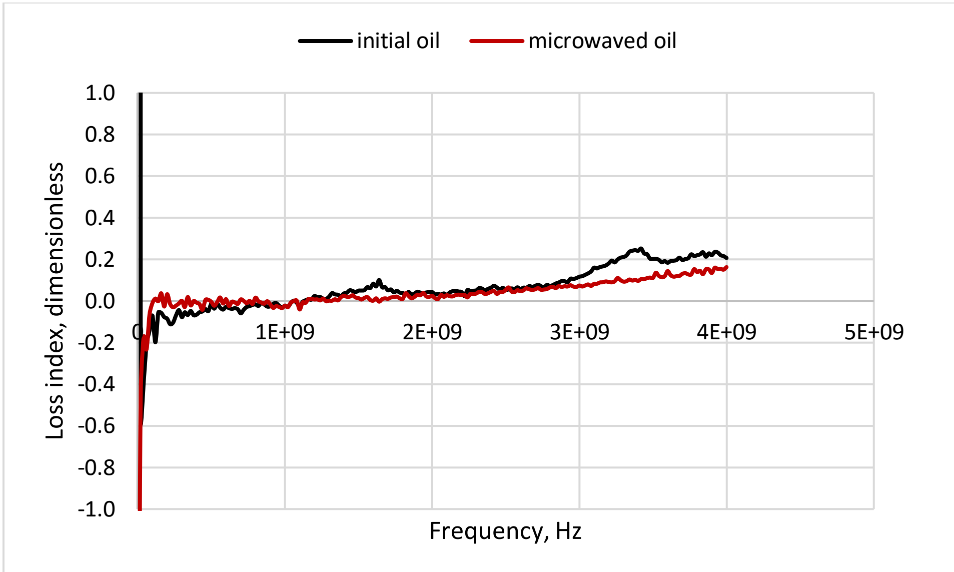


Figure A-57— Loss Index of C3 bulk crude + 10% nC5

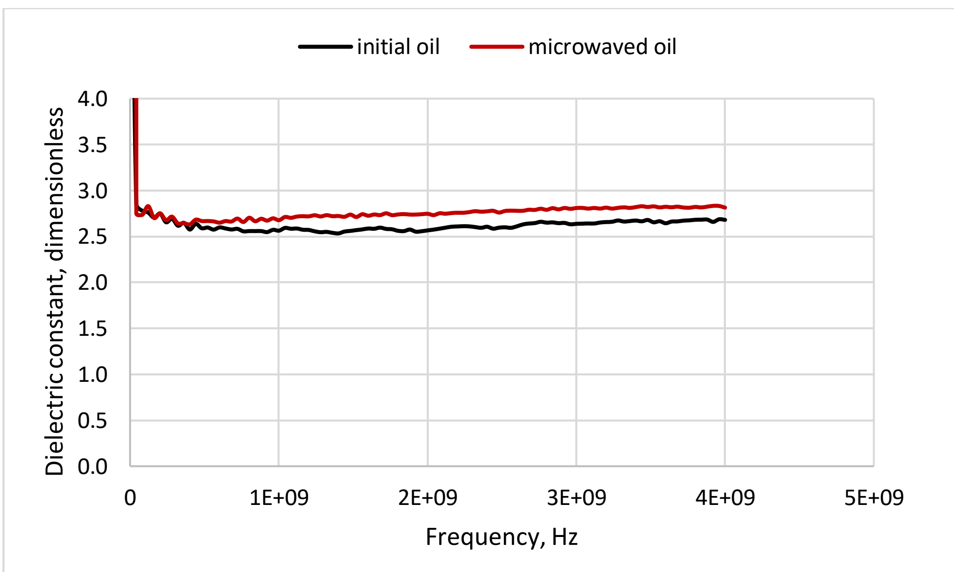


Figure A-58— Dielectric constant of C3 bulk crude + 20% nC5

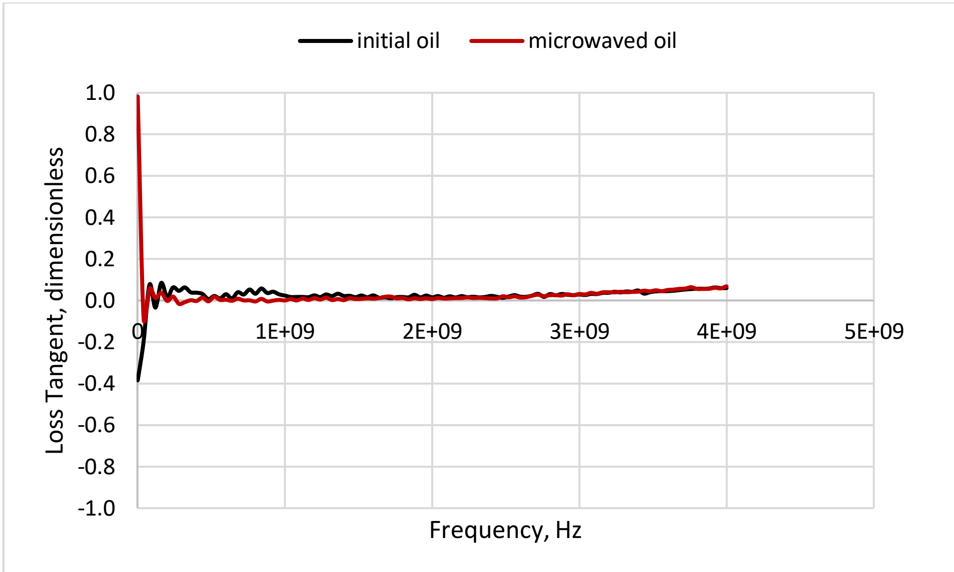


Figure A-59— Loss Tangent of C3 bulk crude + 20% nC5

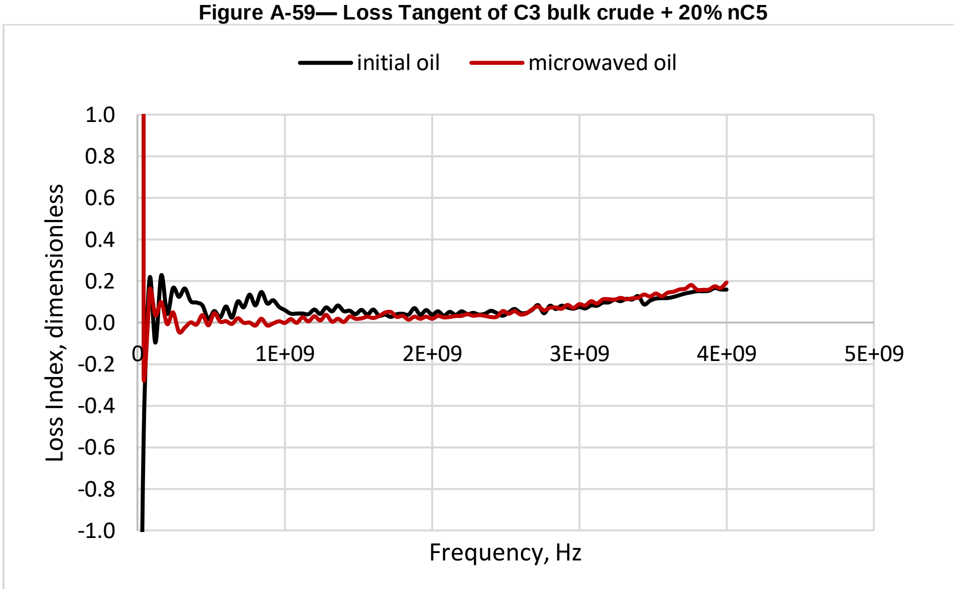


Figure A-60— Loss Index of C3 bulk crude + 20% nC5

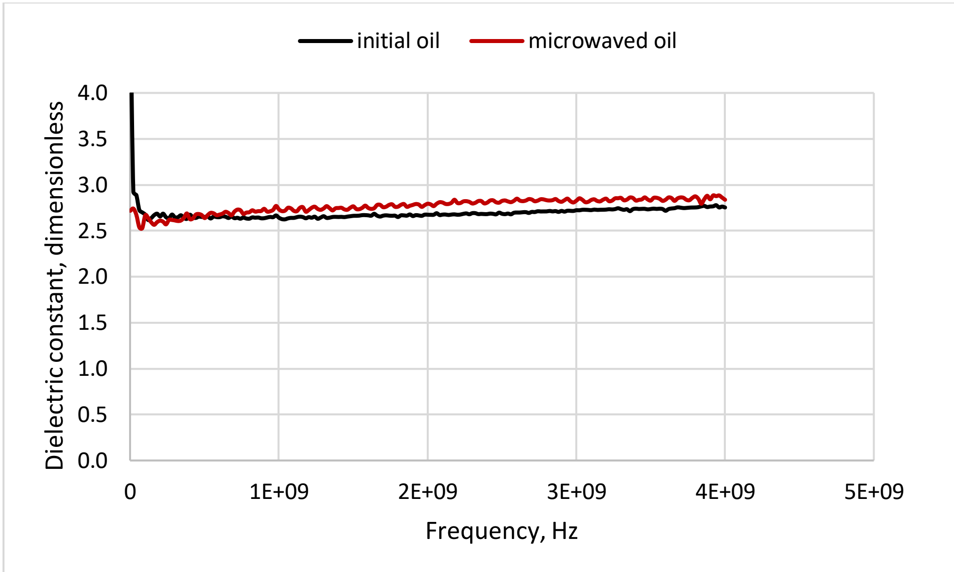


Figure A-61— Dielectric constant of C3 bulk crude + 50% nC5

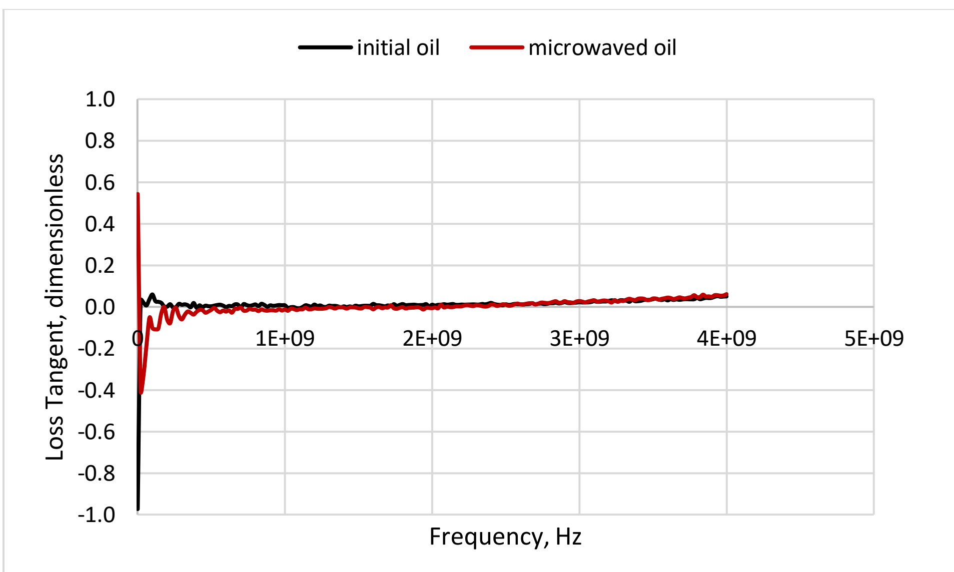


Figure A-62— Loss Tangent of C3 bulk crude + 50% nC5

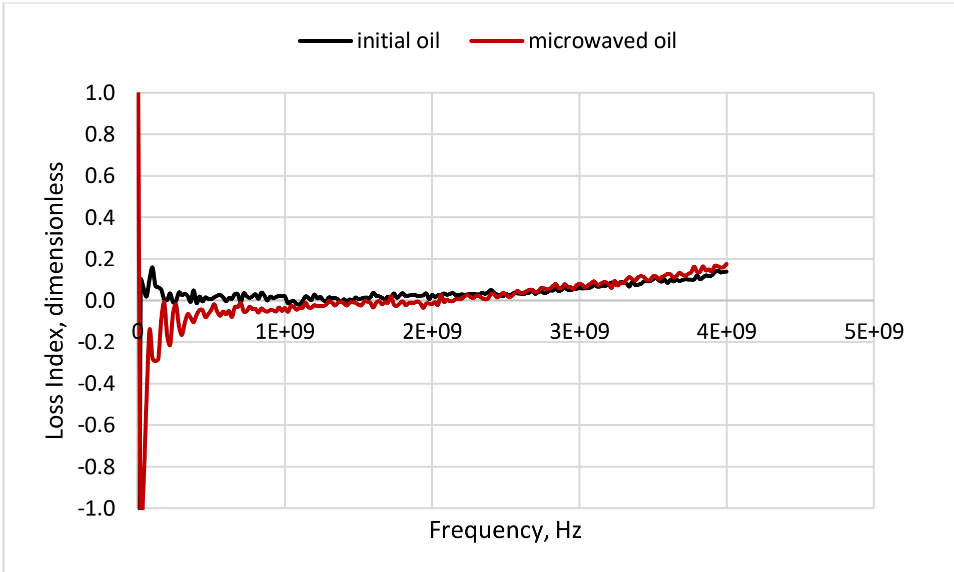


Figure A-63— Loss Index of C3 bulk crude + 50% nC5

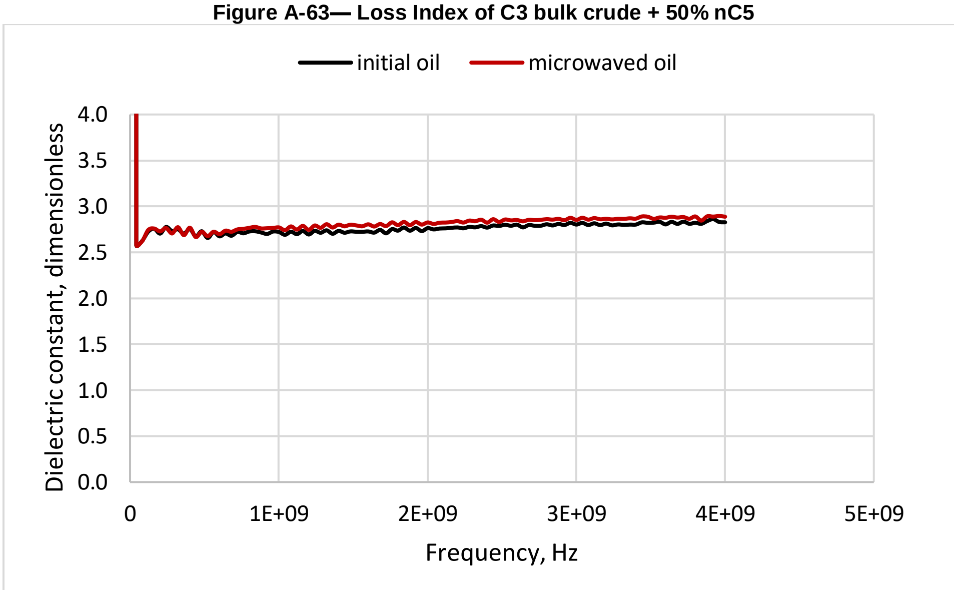


Figure A-64— Dielectric constant of C3 bulk crude + 10% nC7

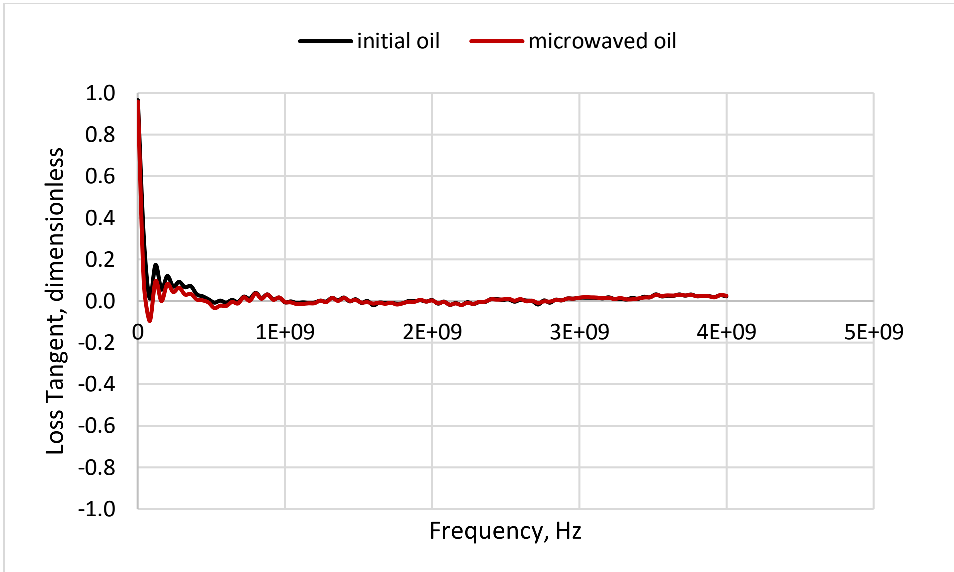


Figure A-65— Loss Tangent of C3 bulk crude + 10% nC7

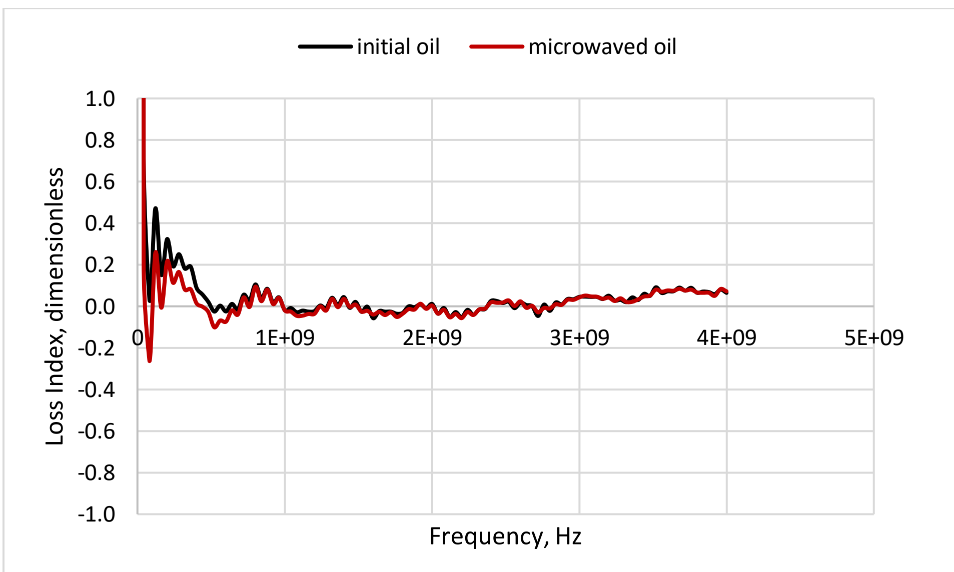


Figure A-66— Loss Index of C3 bulk crude + 10% nC7

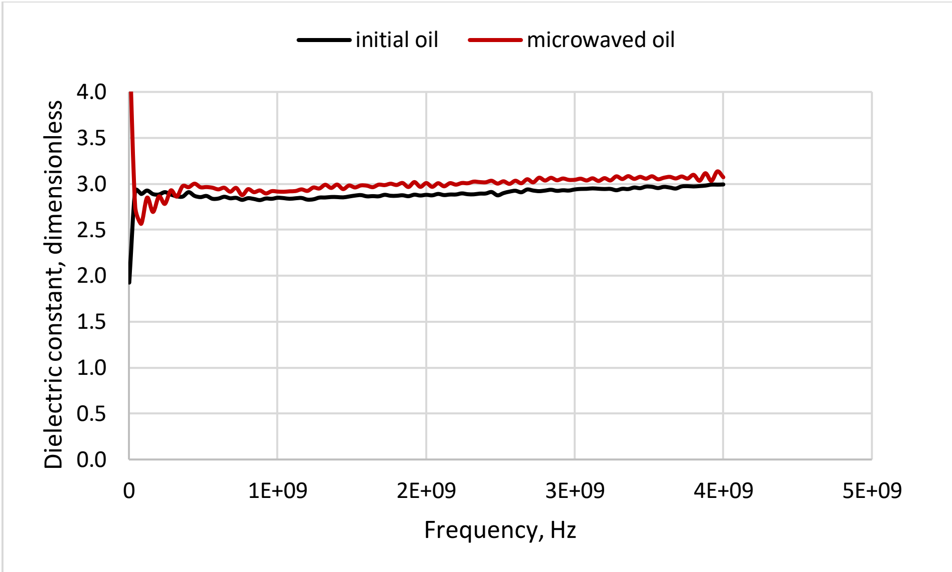


Figure A-67— Dielectric constant of C3 bulk crude + 20% nC7

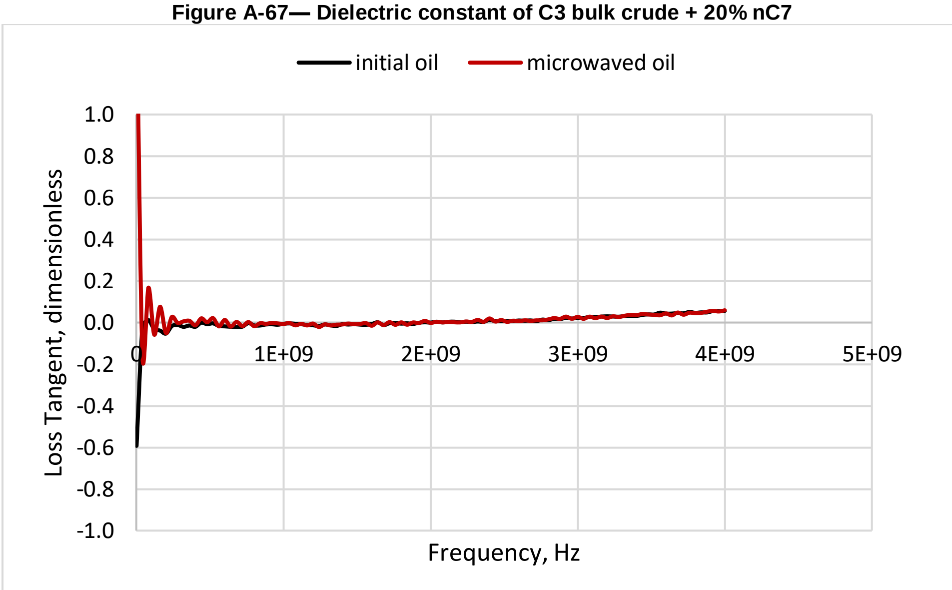


Figure A-68— Loss Tangent of C3 bulk crude + 20% nC7

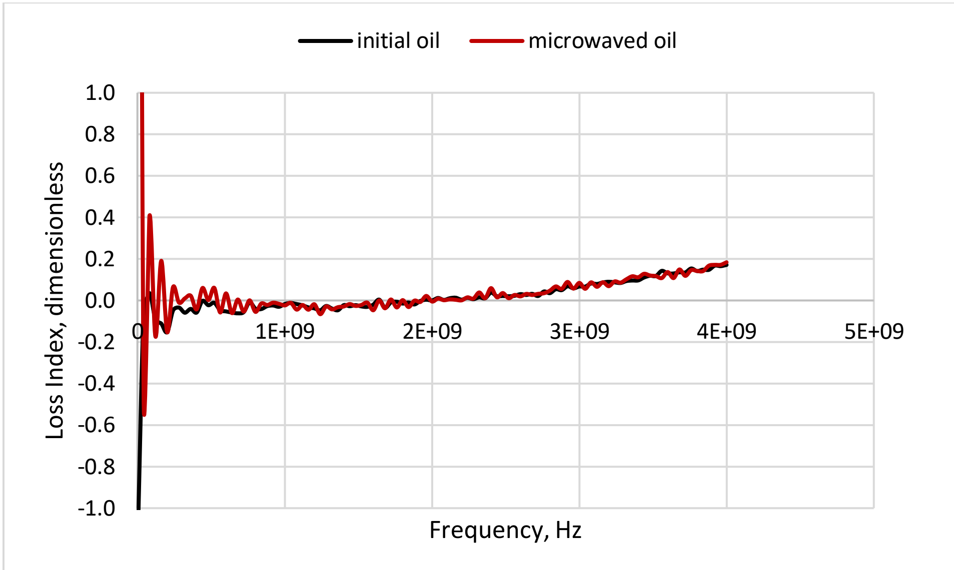


Figure A-69— Loss Index of C3 bulk crude + 20% nC7

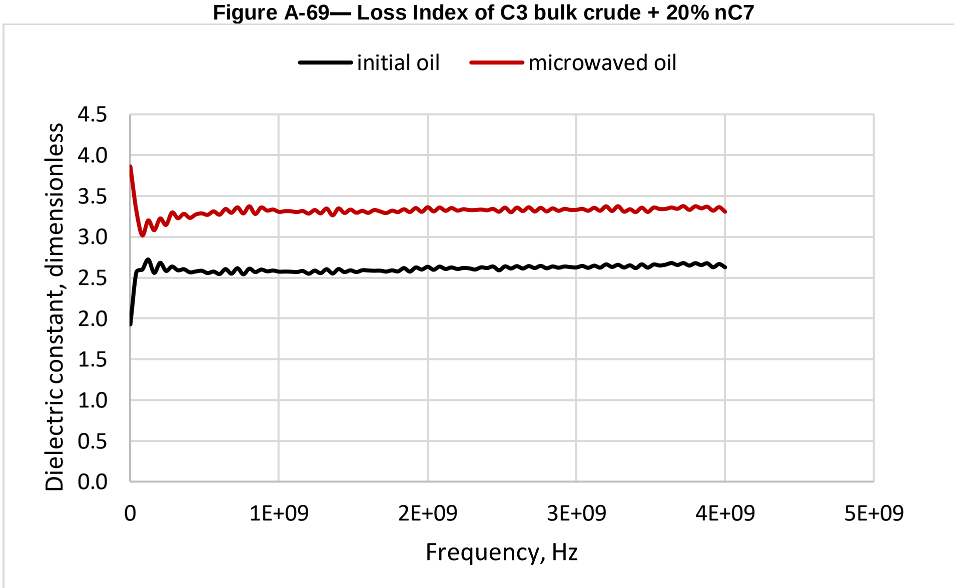


Figure A-70— Dielectric constant of C3 bulk crude + 50% nC7

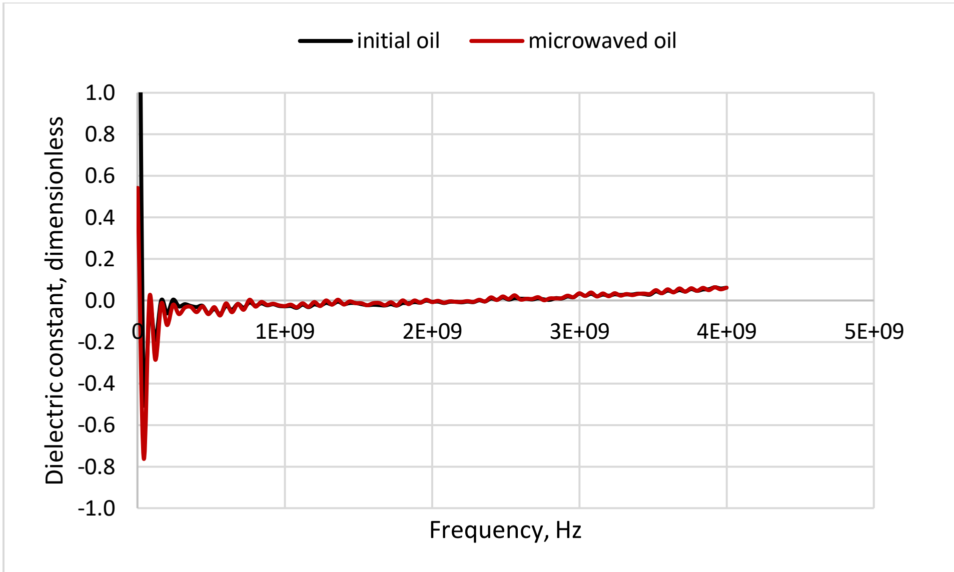


Figure A-71— Loss Tangent of C3 bulk crude + 50% nC7

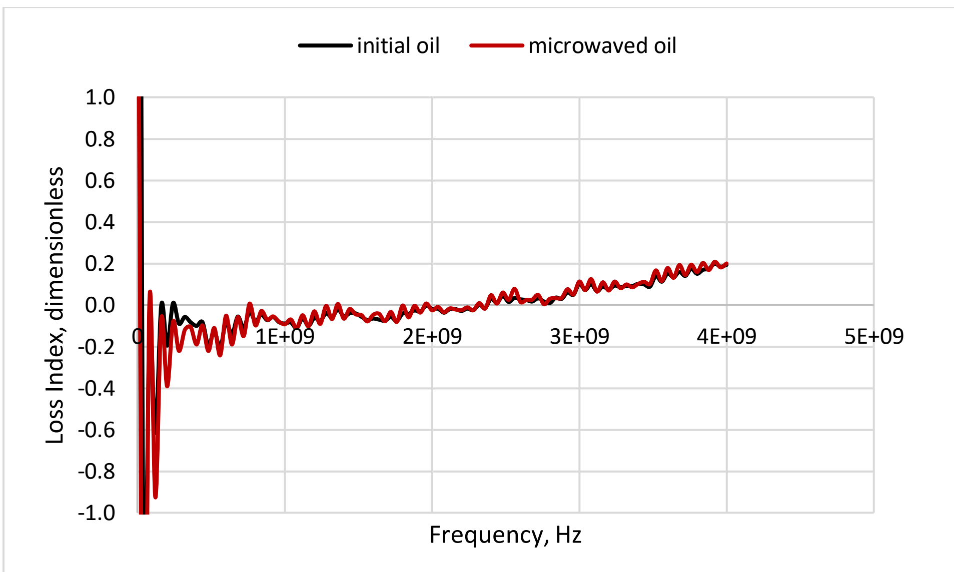


Figure A-72— Loss Index of C3 bulk crude + 50% nC7

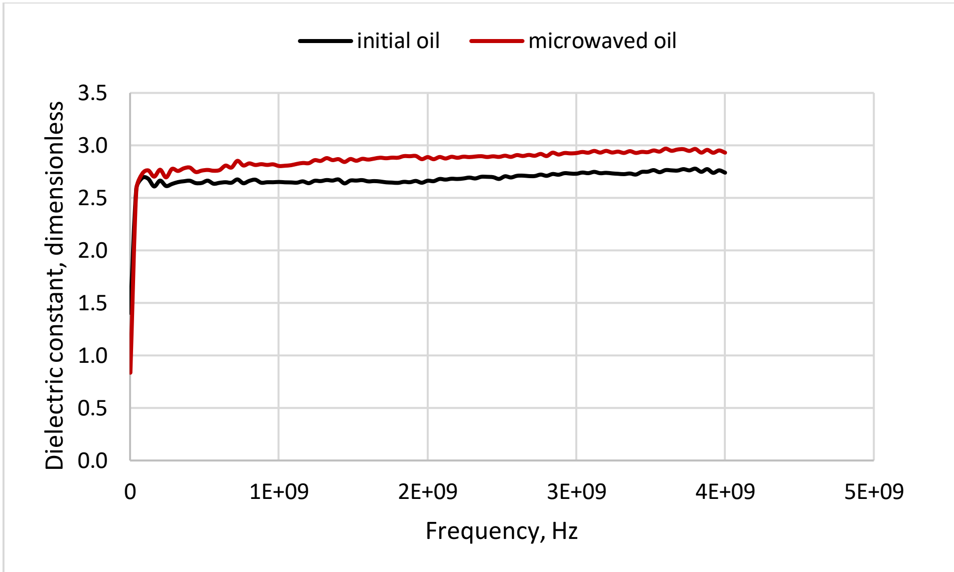


Figure A-73— Dielectric constant of C3 bulk crude + 10% Toluene

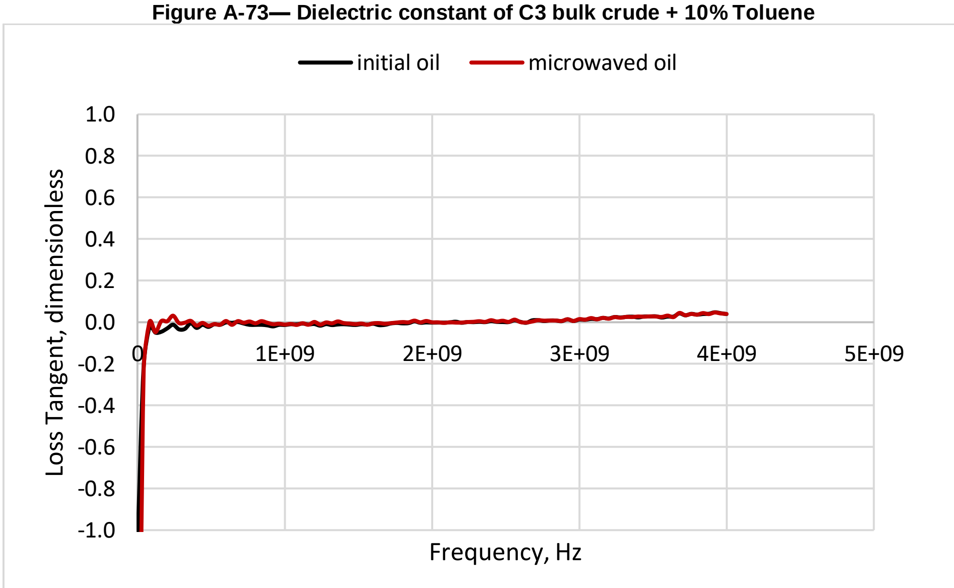


Figure A-74— Loss Tangent of C3 bulk crude + 10% Toluene

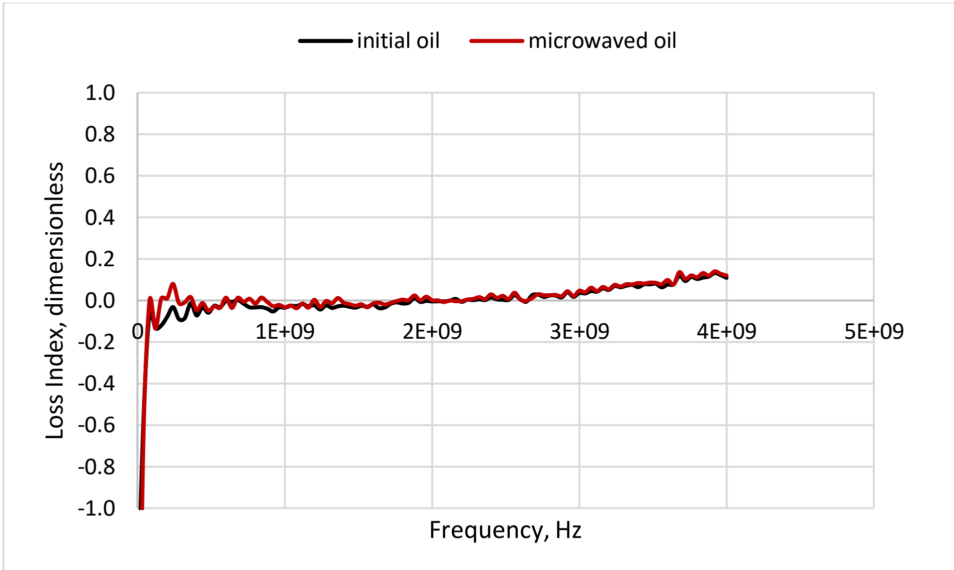


Figure A-75— Loss Index of C3 bulk crude + 10% Toluene

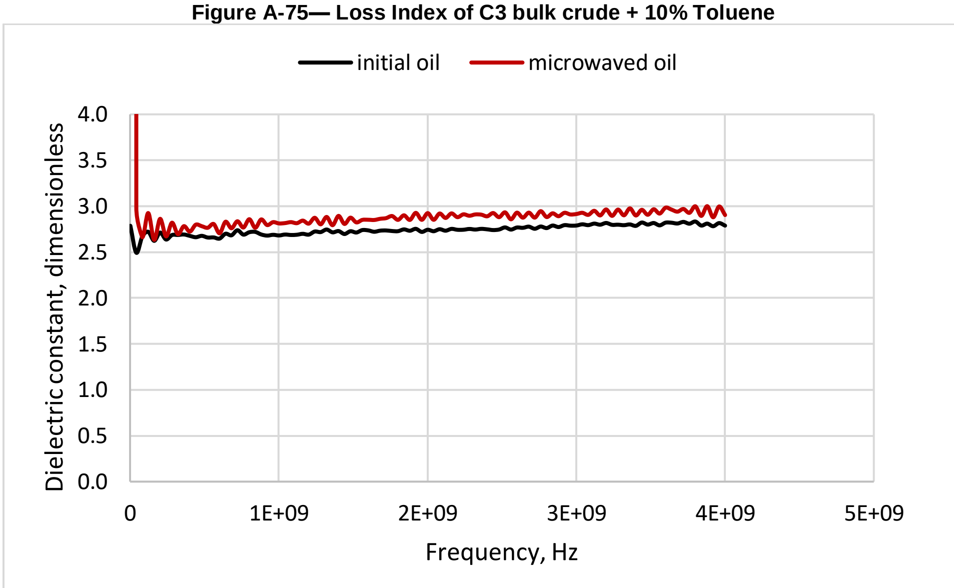


Figure A-76— Dielectric constant of C3 bulk crude + 20% Toluene

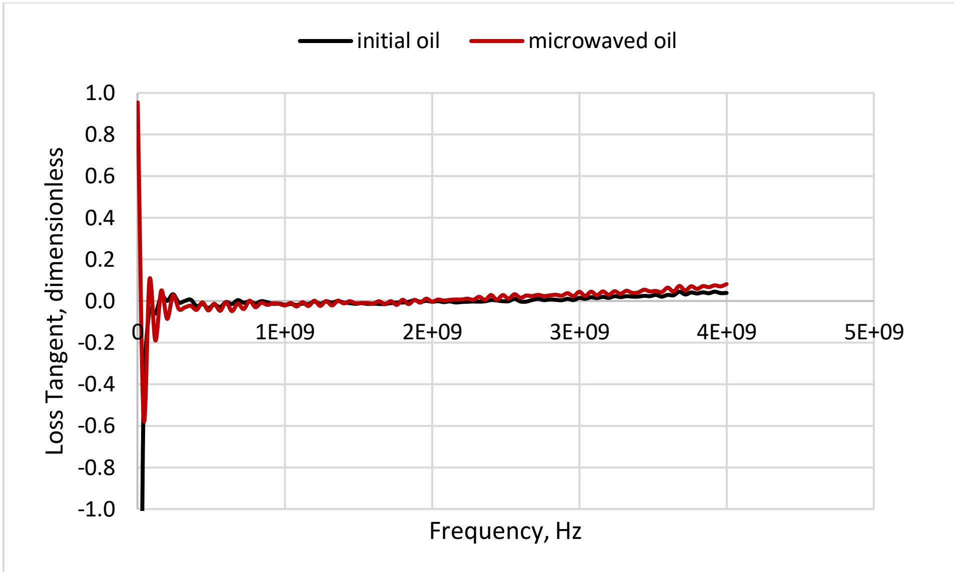


Figure A-77— Loss Tangent of C3 bulk crude + 20% Toluene

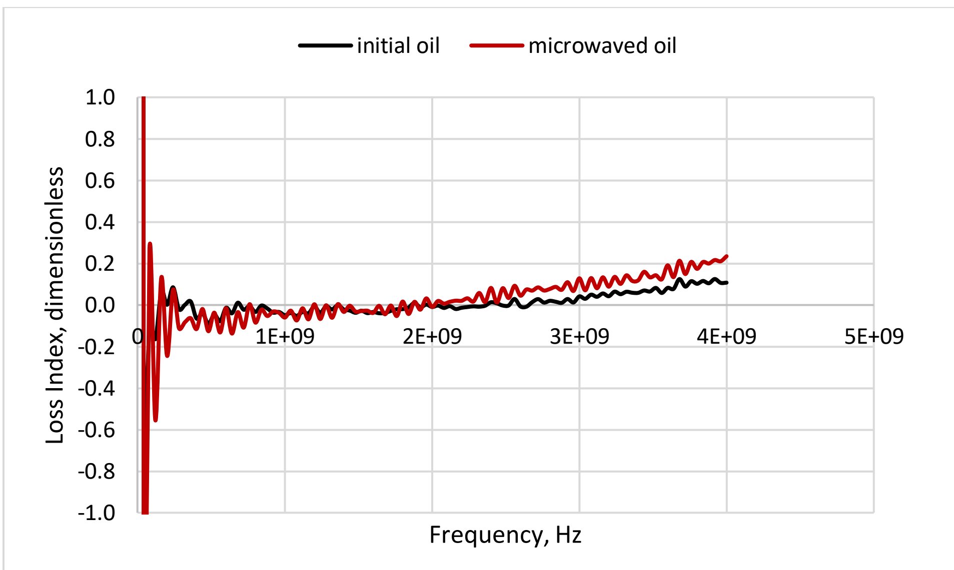


Figure A-78— Loss Index of C3 bulk crude + 20% Toluene

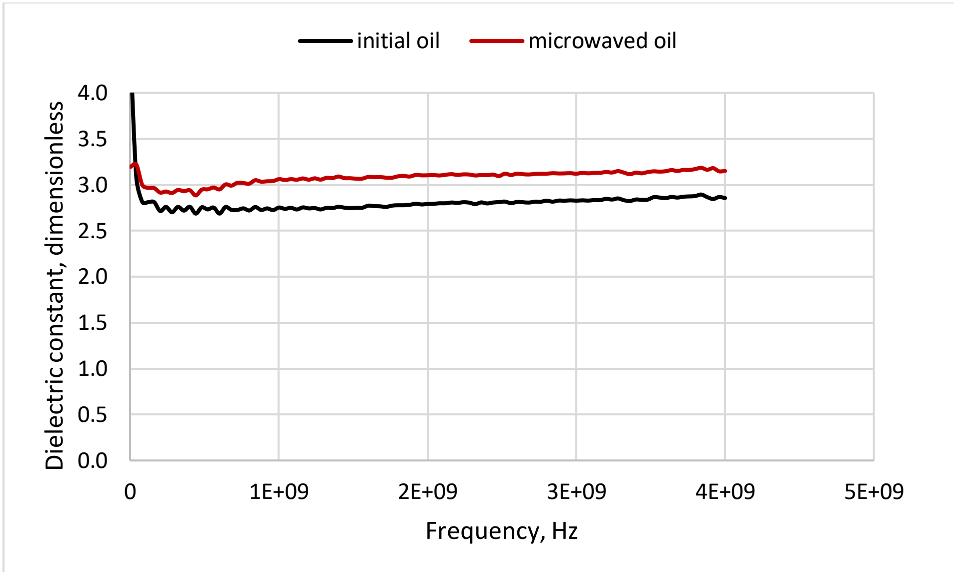


Figure A-79— Dielectric constant of C3 bulk crude + 50% Toluene

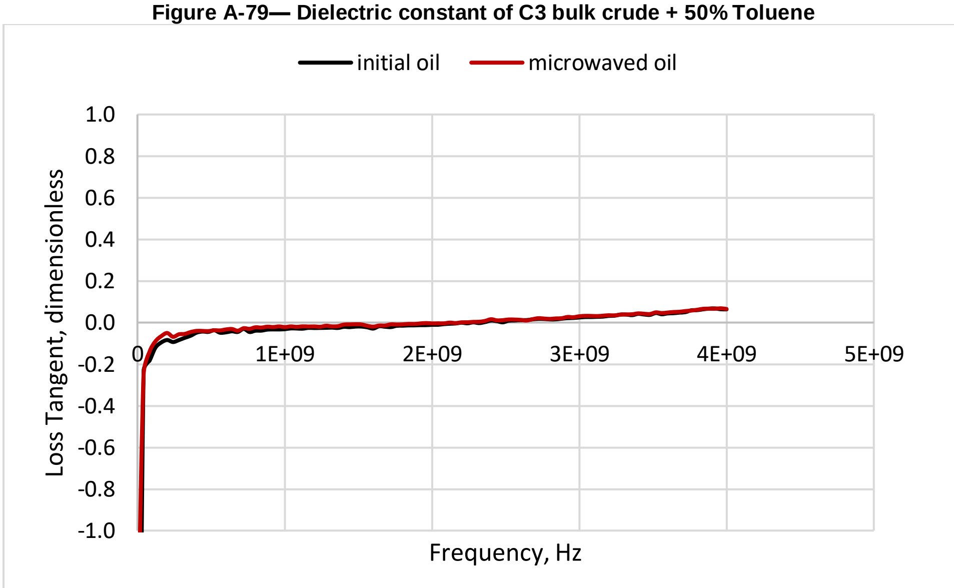


Figure A-80— Loss Tangent of C3 bulk crude + 50% Toluene

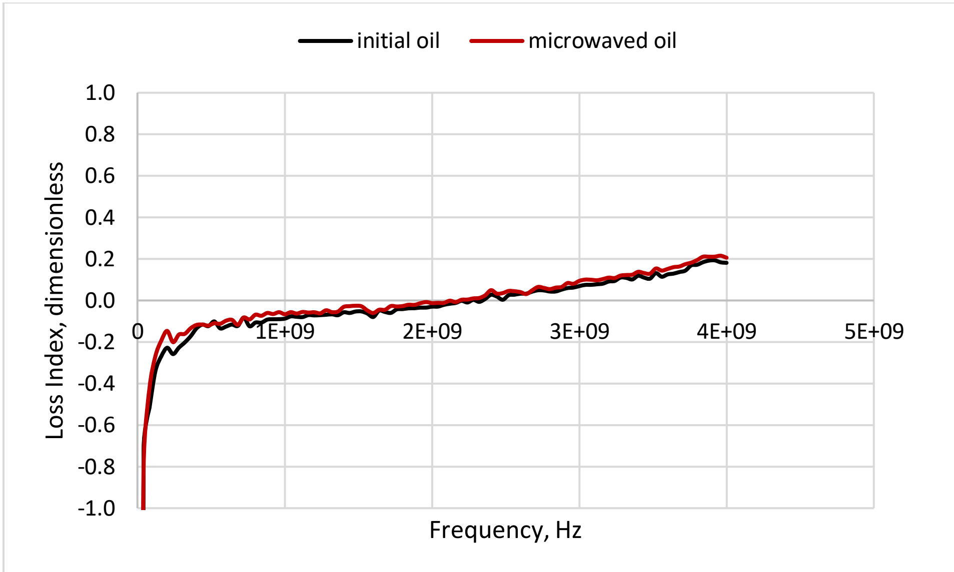
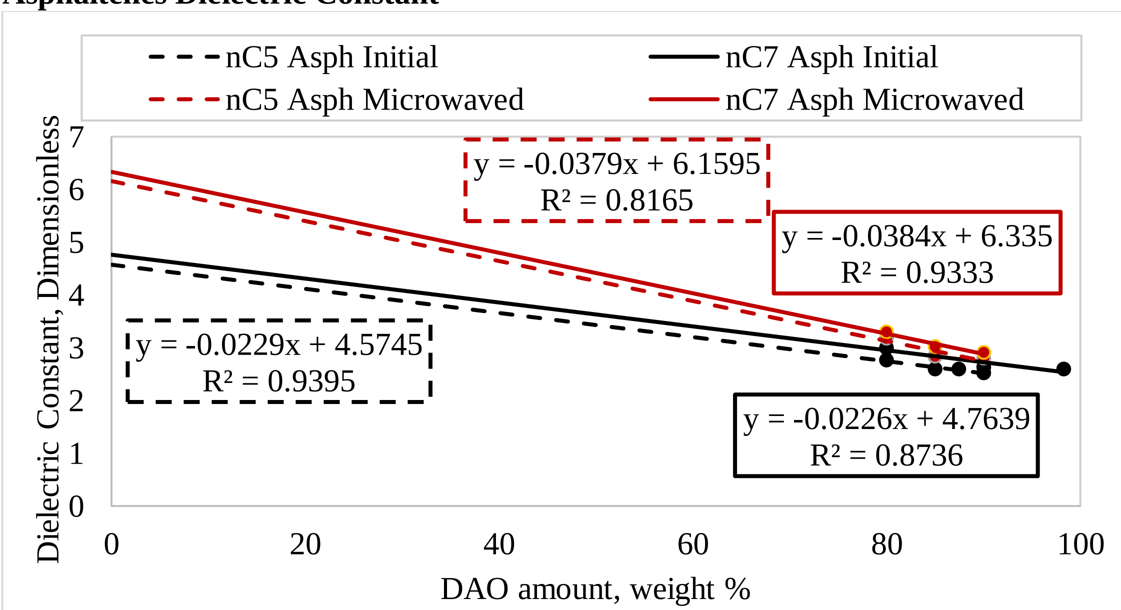


Figure A-81— Loss Index of C3 bulk crude + 50% Toluene

Asphaltenes Dielectric Constant



A-82— Estimation of crude oil C2 insoluble asphaltenes dielectric constants for nC5 and nC7 by extrapolation of varying weight percentages of deasphalted oil (DAO)

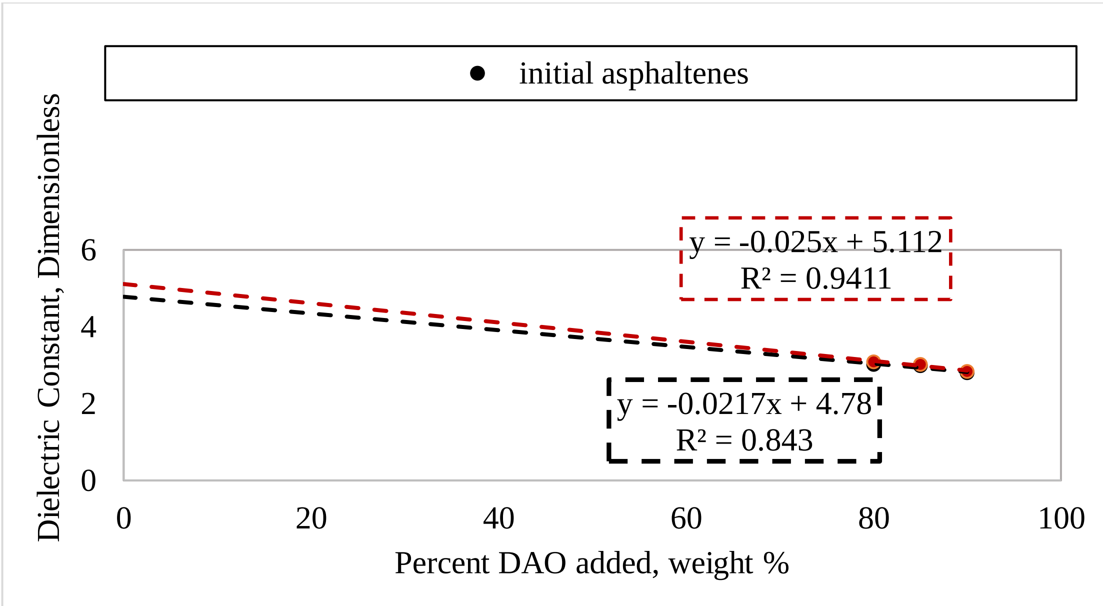


Figure A-83— Estimation of crude oil C1 insoluble asphaltenes dielectric constants for nC5 by extrapolation of varying weight percentages of deasphalted oil (DAO)

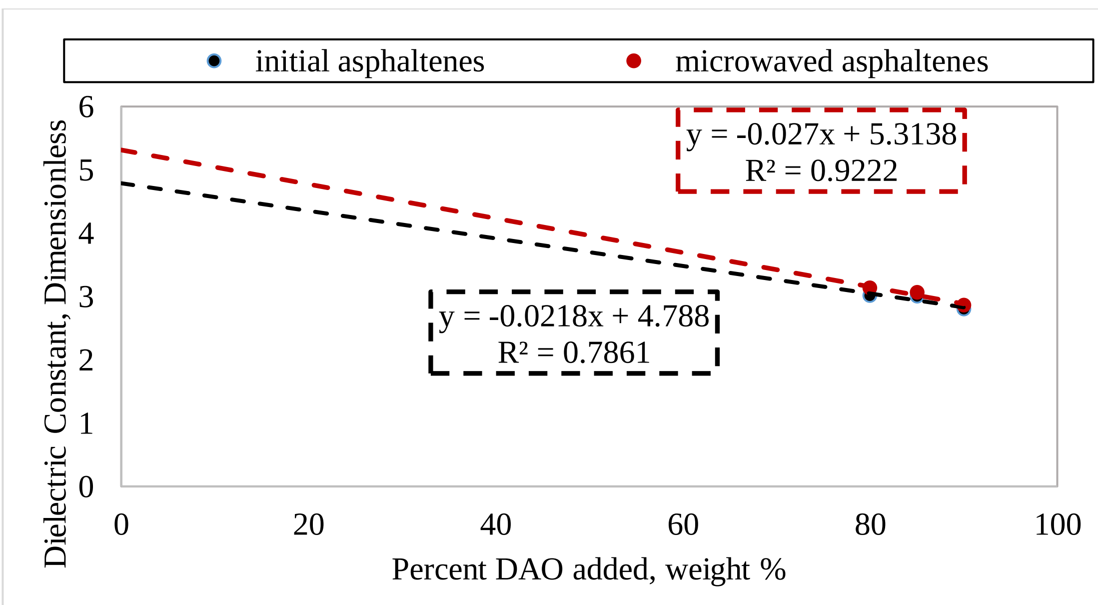


Figure A-84— Estimation of crude oil C3 insoluble asphaltenes dielectric constants for nC5 by extrapolation of varying weight percentages of deasphalted oil (DAO)

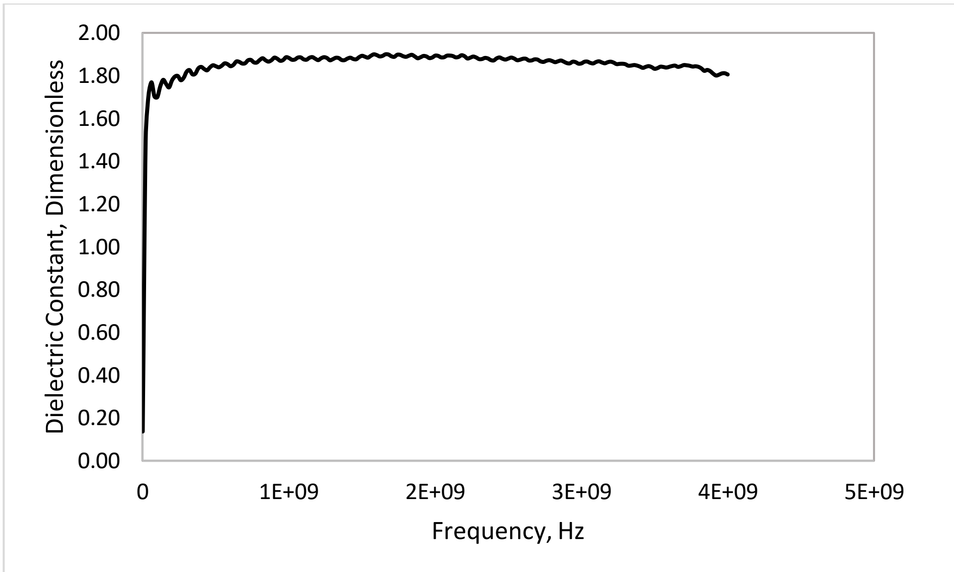


Figure A-85— Dielectric Constant of precipitant solvent nC5

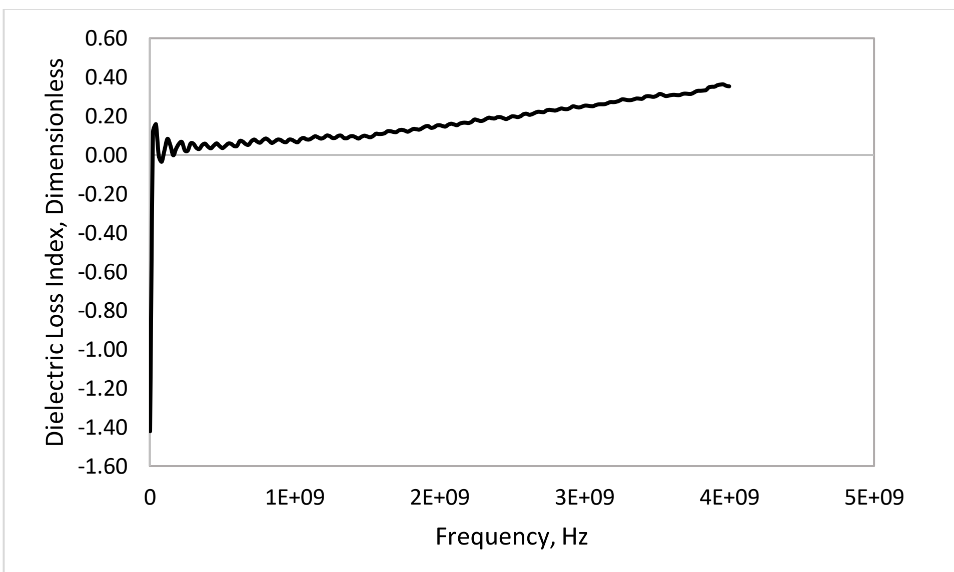


Figure A-86— Dielectric Loss Index of precipitant solvent nC5

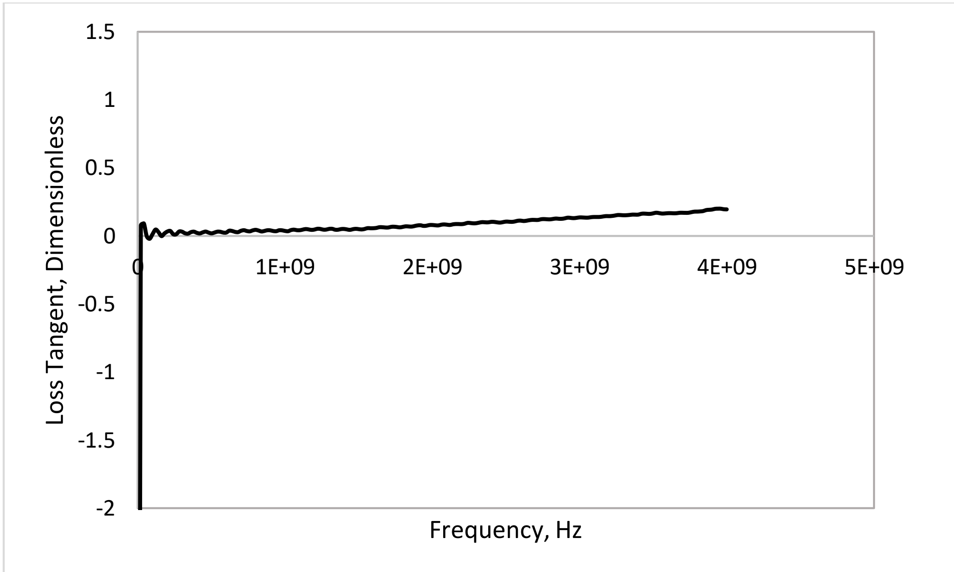


Figure A-87— Dielectric Loss Tangent of precipitant solvent nC5

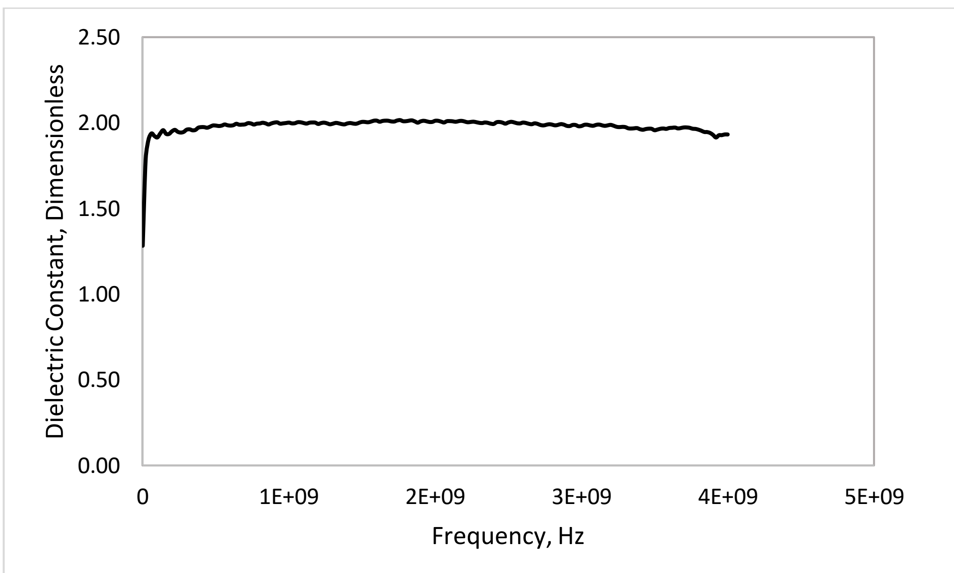


Figure A-88— Dielectric Constant of precipitant solvent nC7

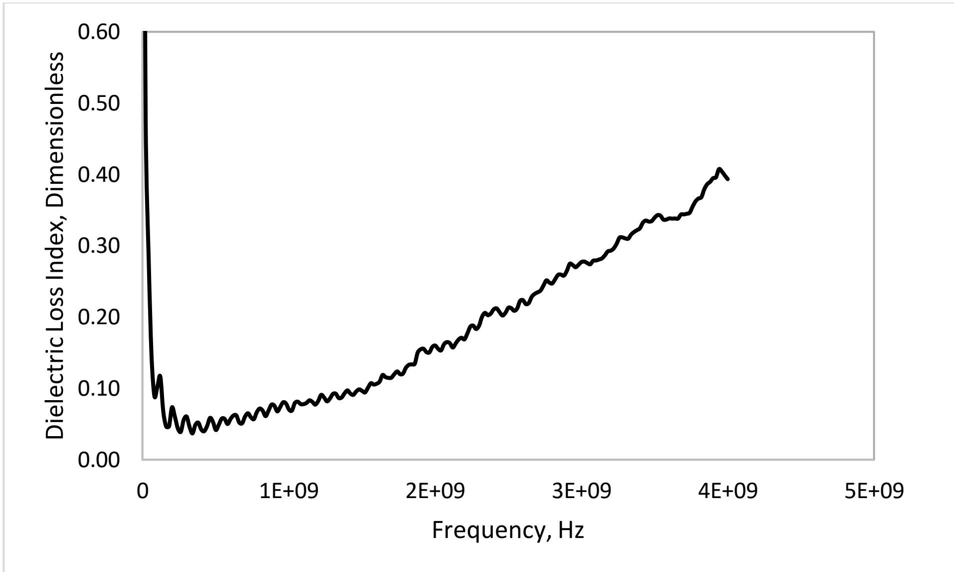


Figure A-89— Dielectric Loss Index of precipitant solvent nC7

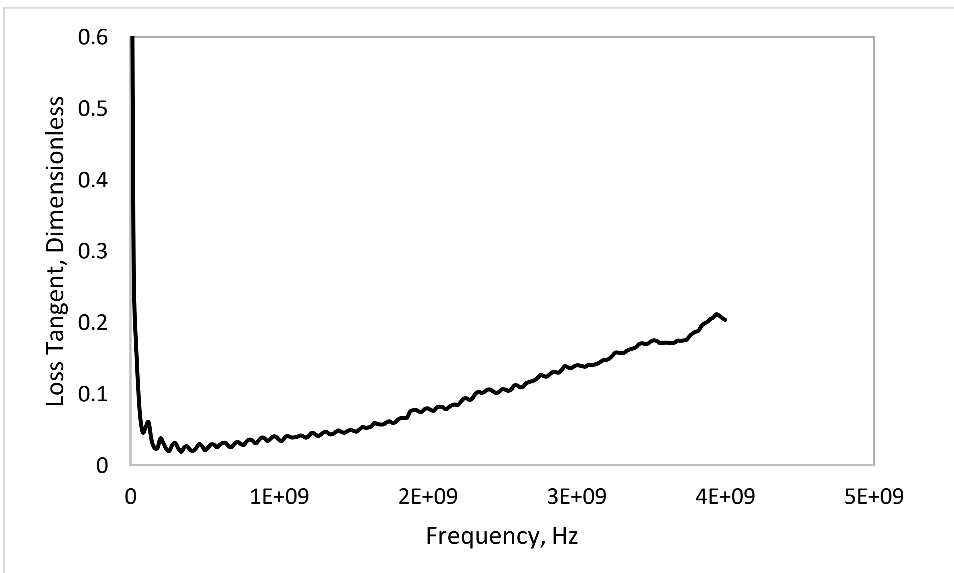


Figure A-90— Dielectric Loss Tangent of precipitant solvent nC7

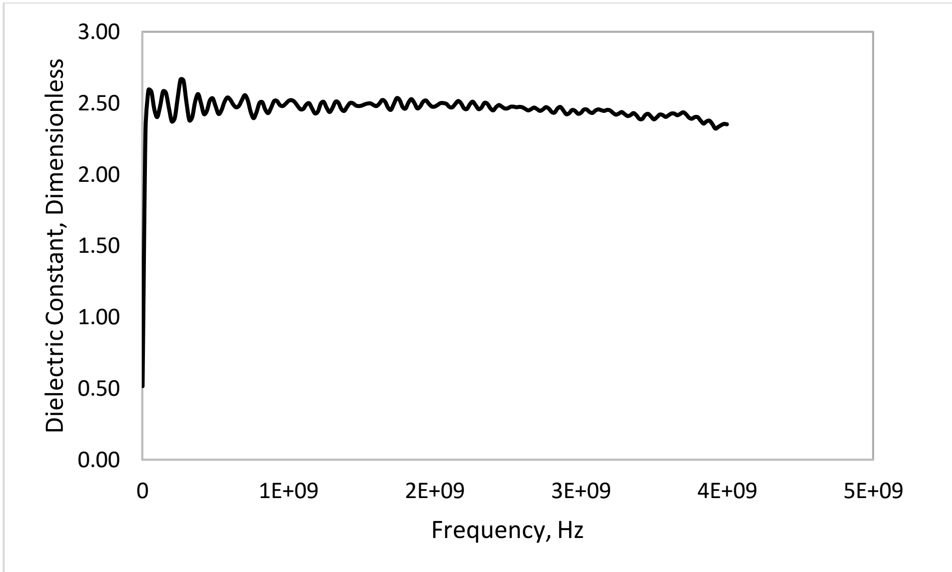


Figure A-91— Dielectric Constant of dispersant solvent toluene

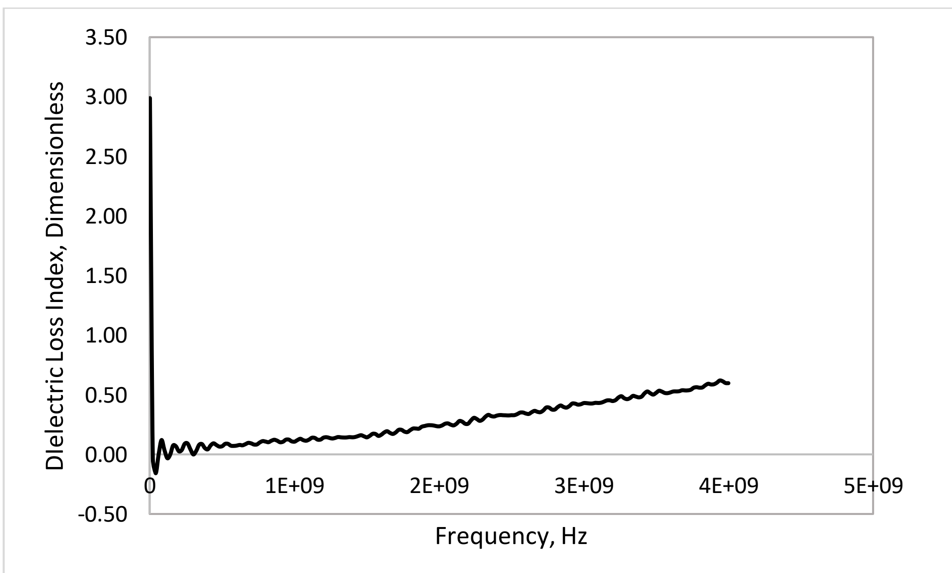


Figure A-92— Dielectric Loss Index of dispersant solvent toluene

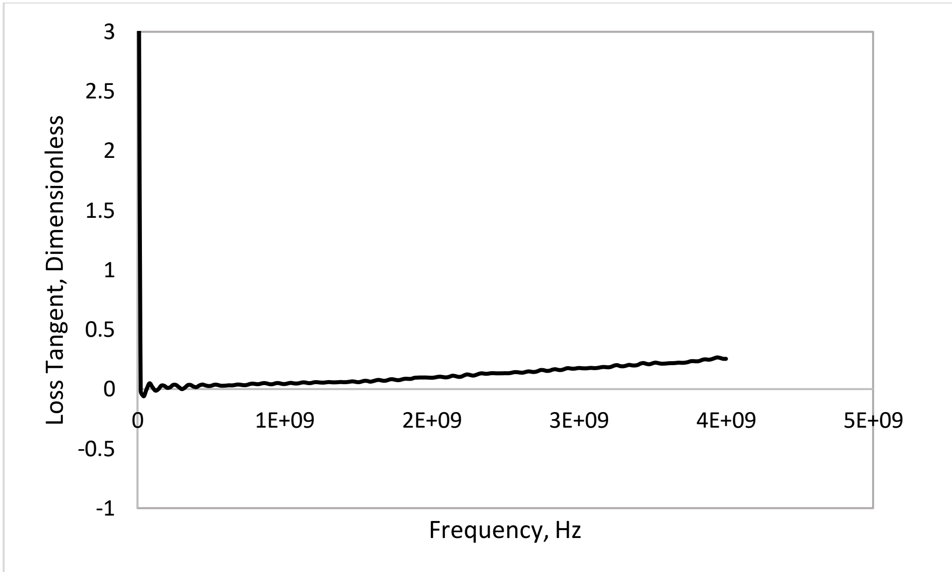


Figure A-93— Dielectric Loss Tangent of dispersant solvent toluene

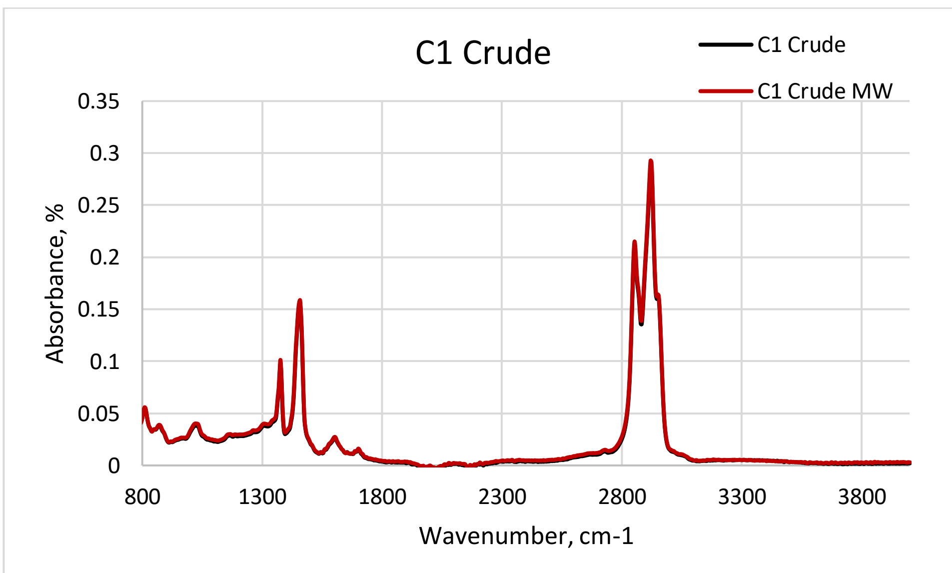


Figure A-94— FTIR results of bulk oil C1

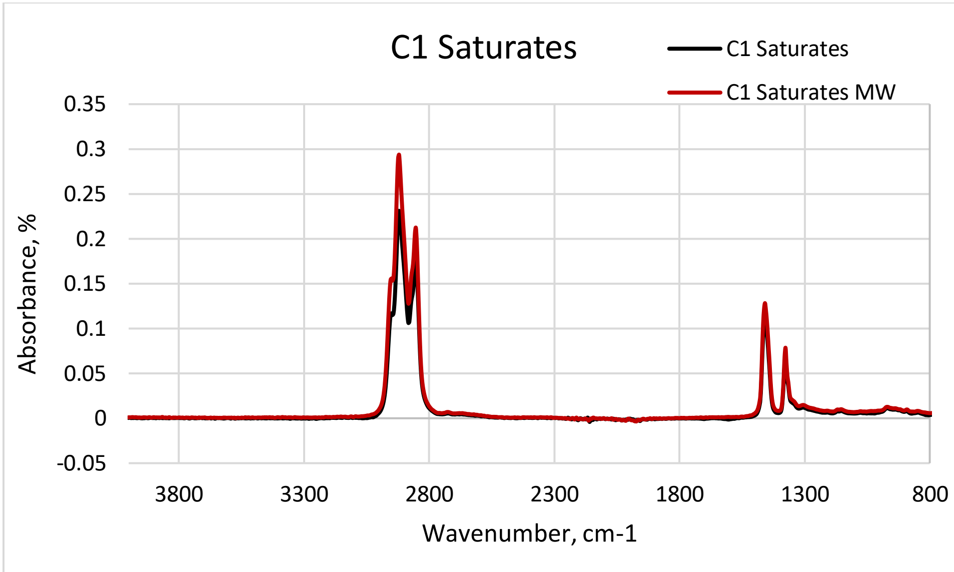


Figure A-95— FTIR results of C1 Saturates fraction

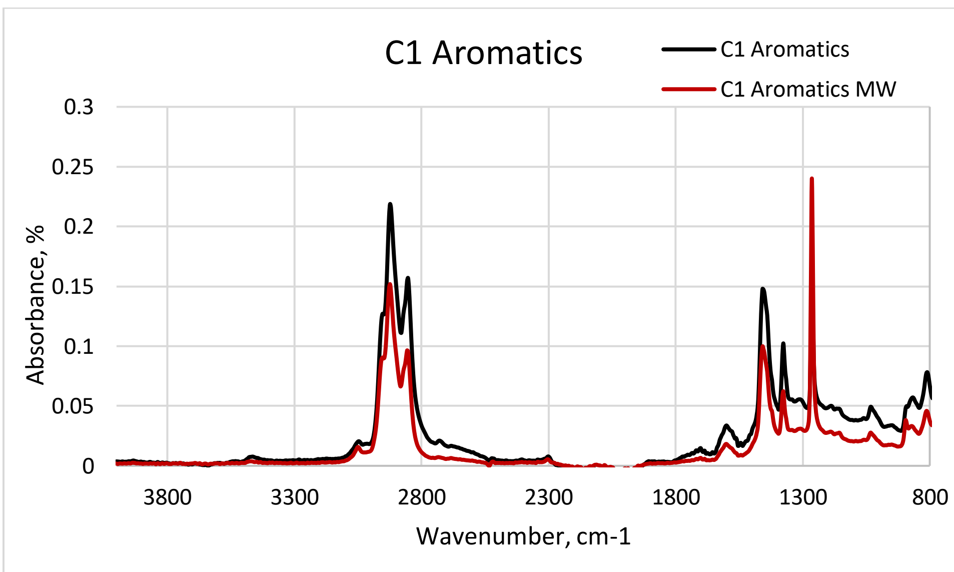


Figure A-96— FTIR results of C1 Aromatics fraction

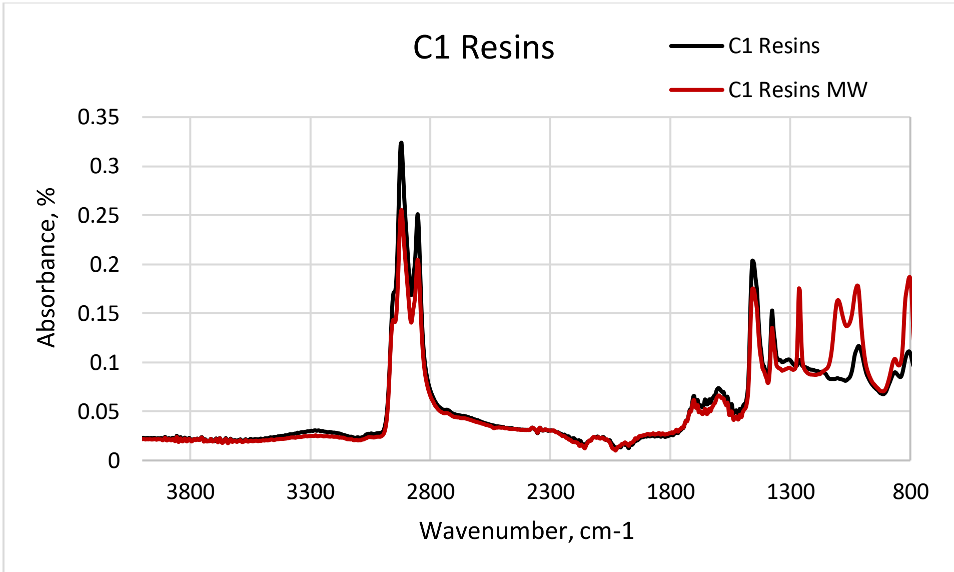


Figure A-97— FTIR results of C1 resins fraction

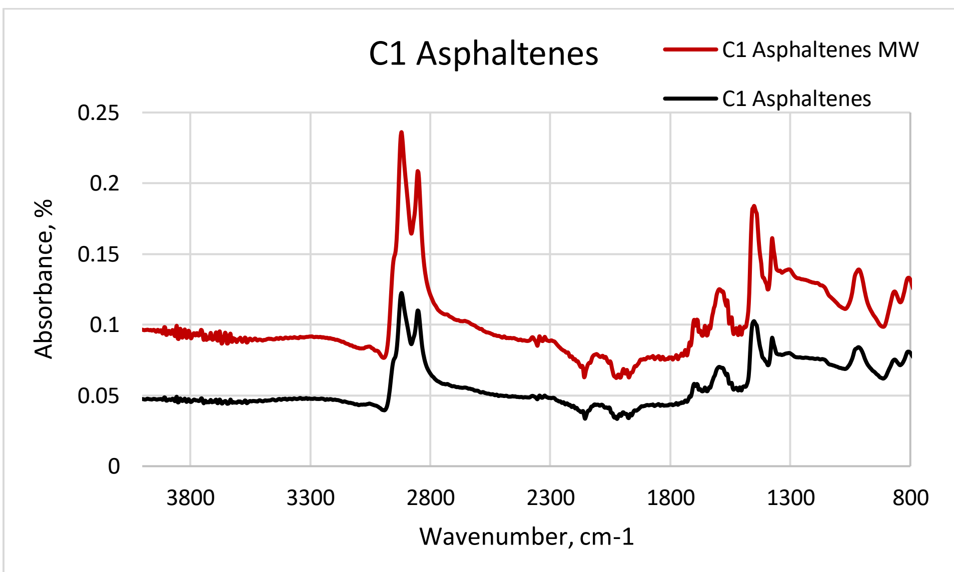


Figure A-98— FTIR results of C1 Asphaltenes fraction

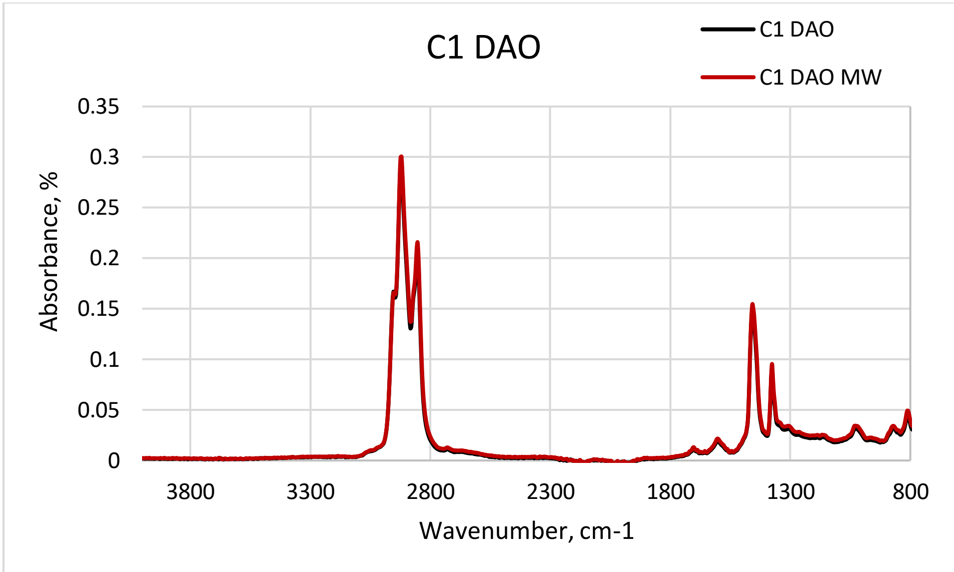


Figure A-99— FTIR results of C1 DAO

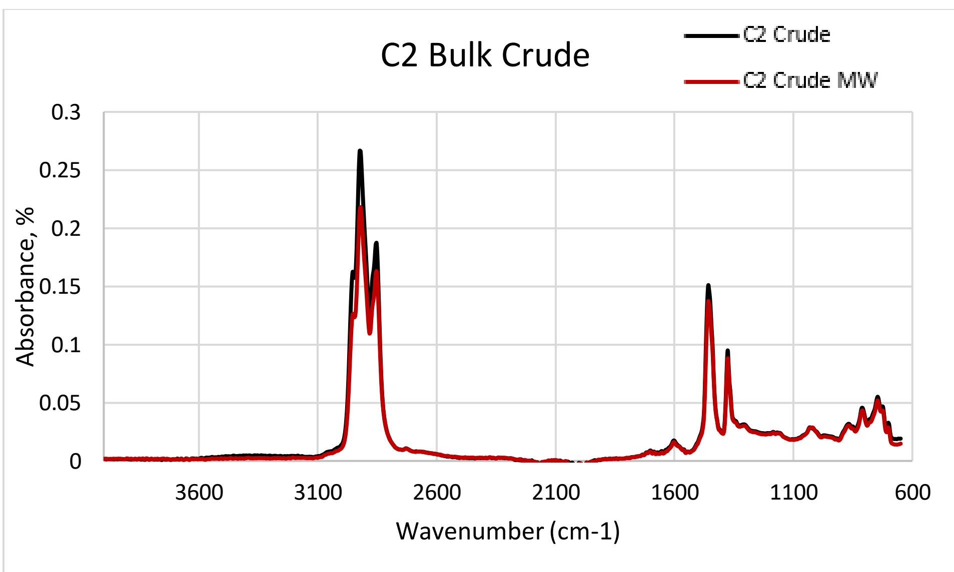


Figure A-100— FTIR results of bulk oil C2

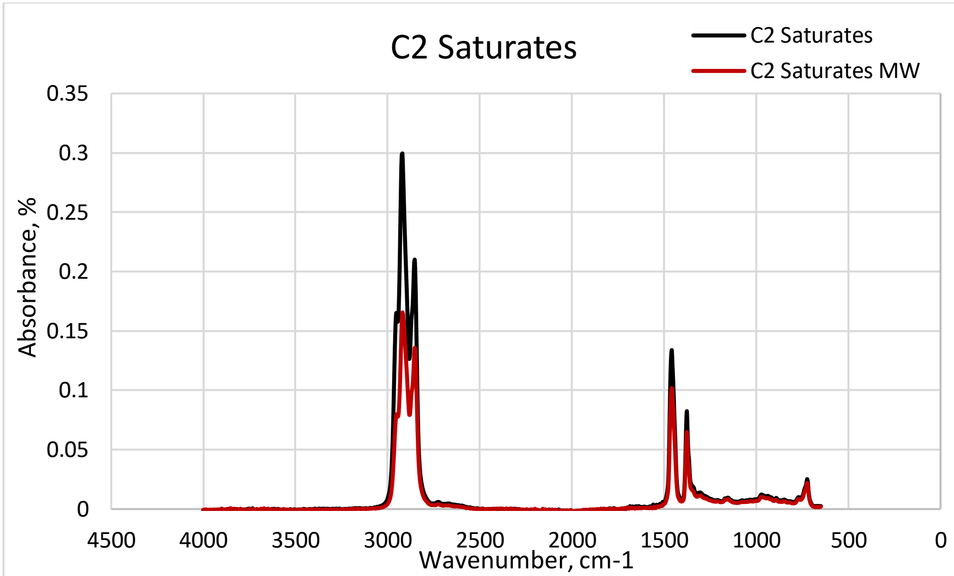


Figure A-101— FTIR results of C2 Saturates Fraction

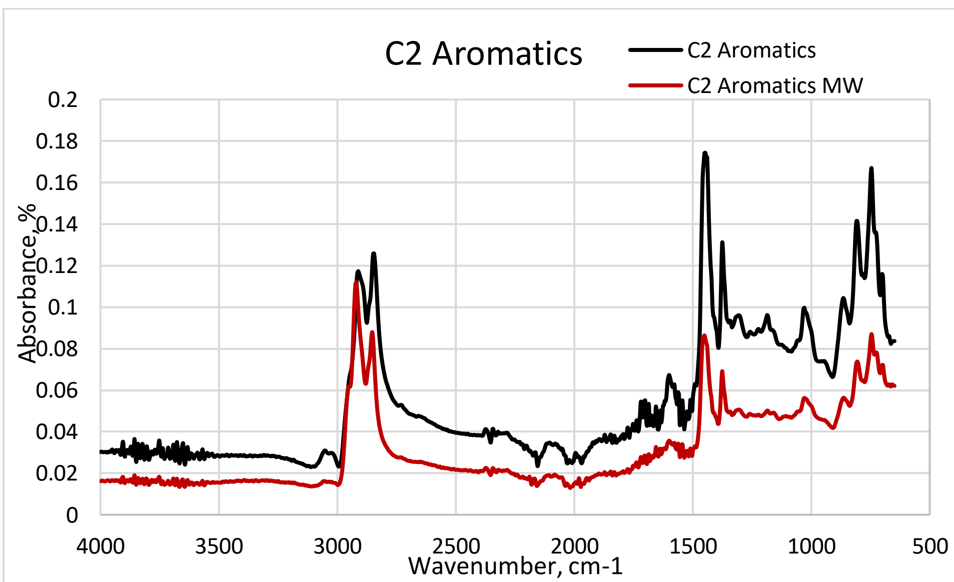


Figure A-102— FTIR results of C2 Aromatics Fraction

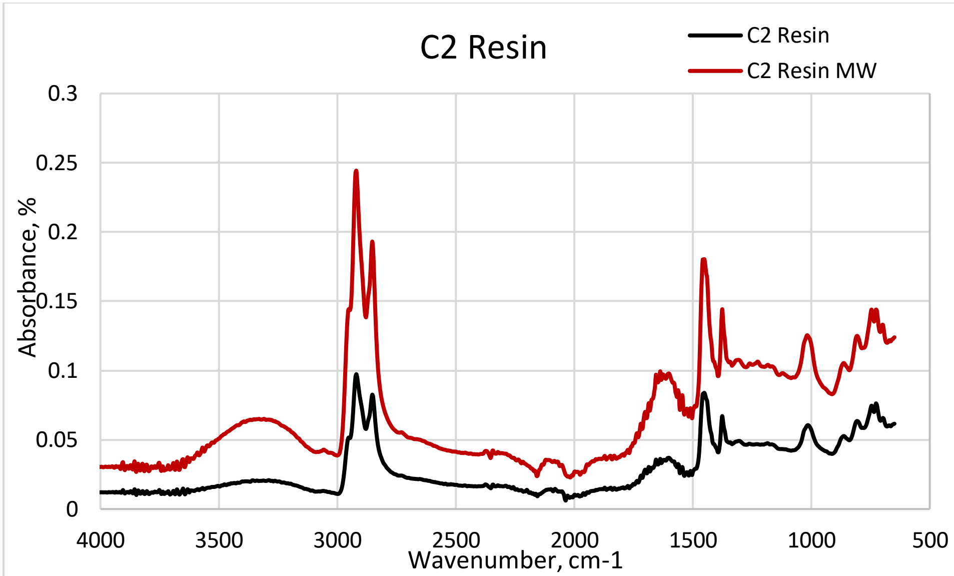


Figure A-103— FTIR results of C2 Resins Fraction

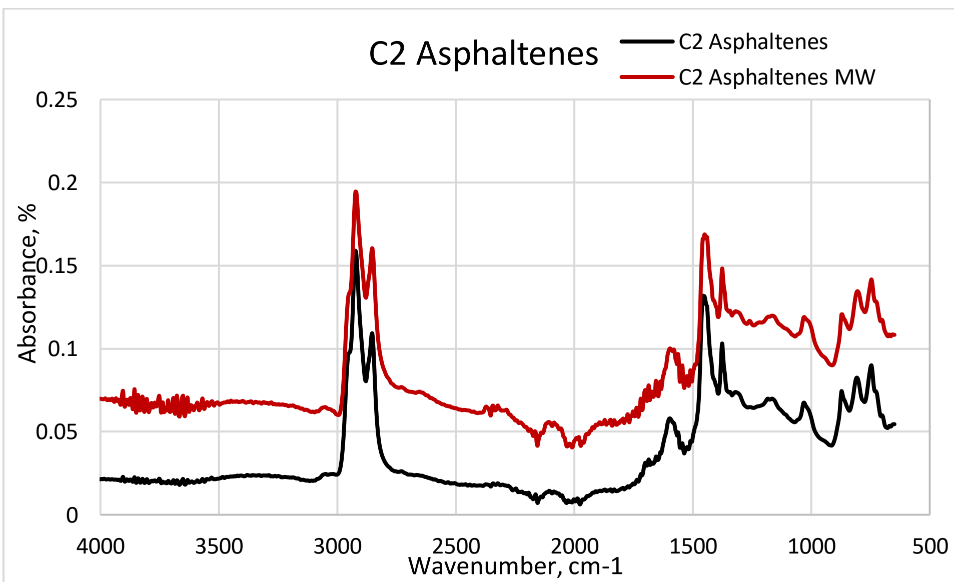


Figure A-104— FTIR results of C2 Asphaltenes Fraction

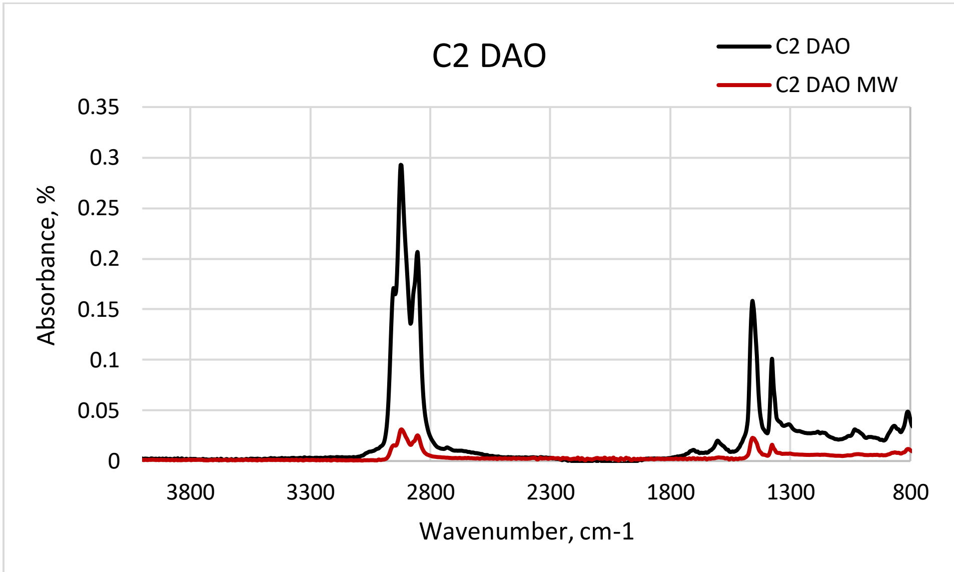


Figure A-105— FTIR results of C2 DAO

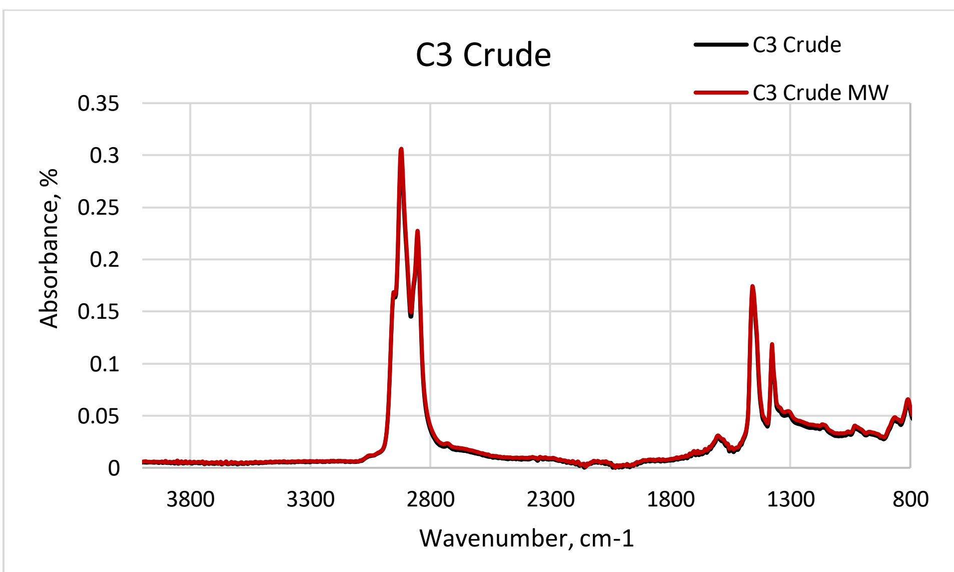


Figure A-106— FTIR results of bulk oil C3

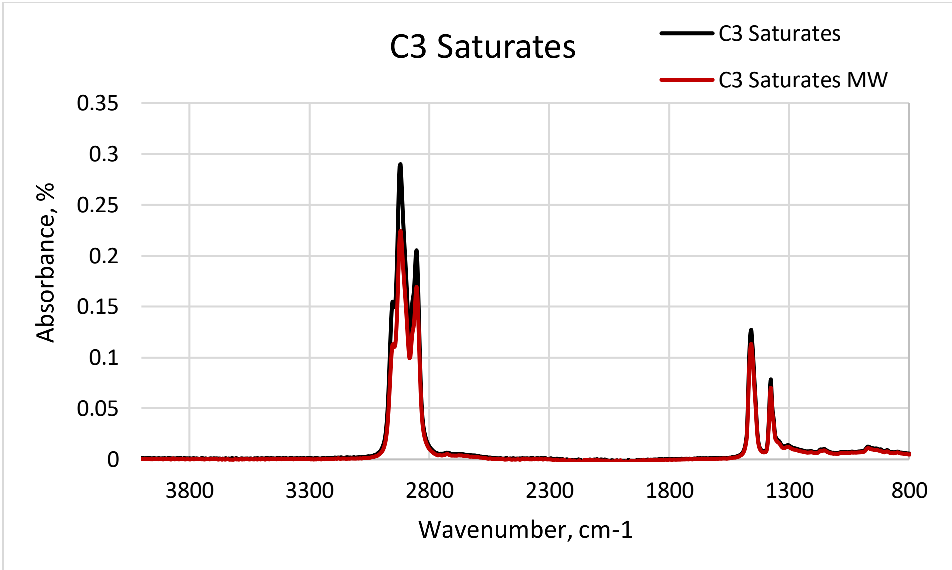


Figure A-107— FTIR results of C3 Saturates fraction

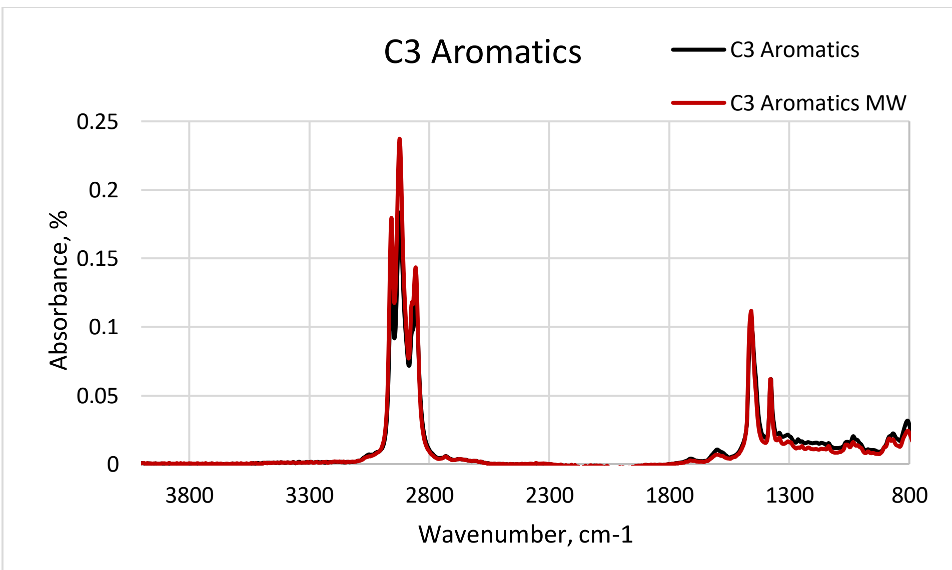


Figure A-108— FTIR results of C3 Aromatics fraction

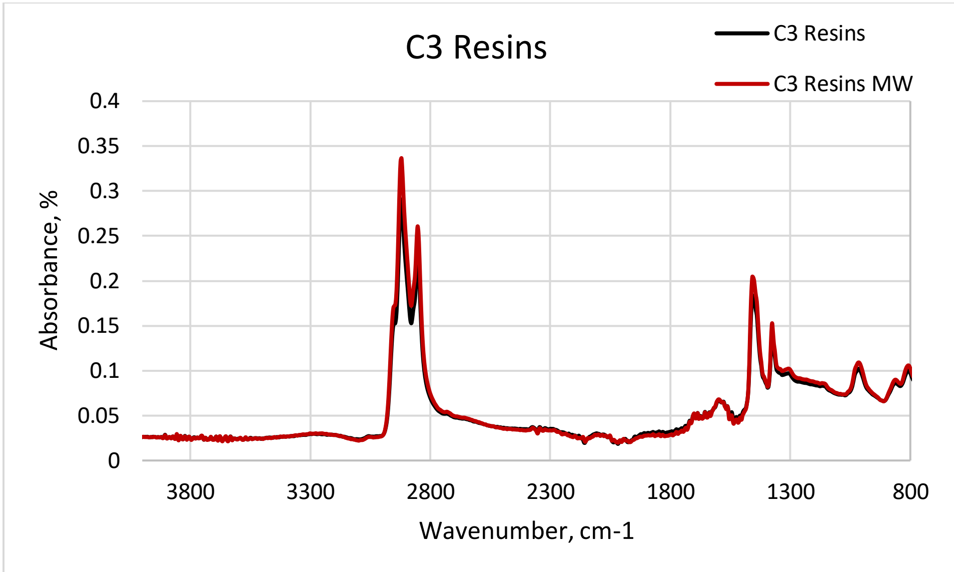


Figure A-109— FTIR results of C3 Resins fraction

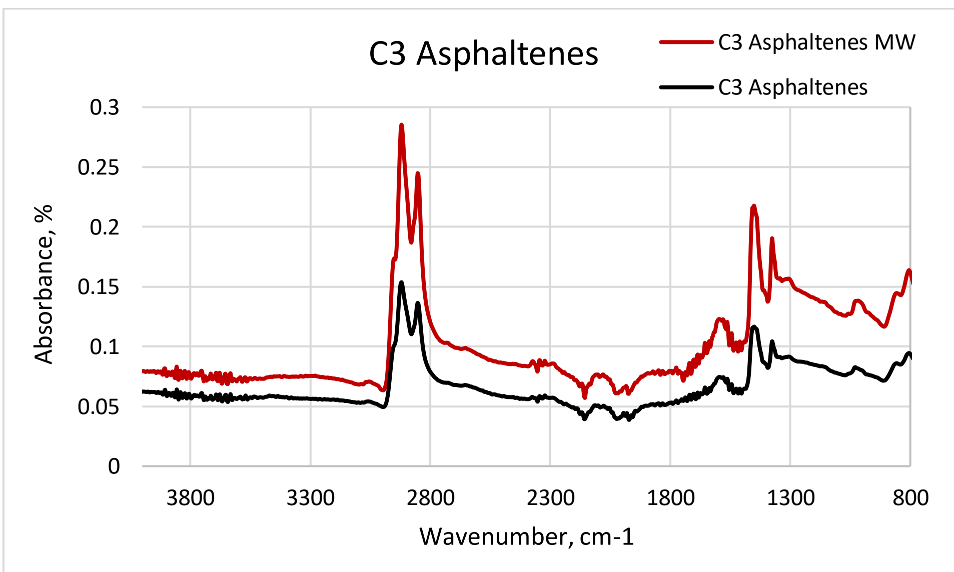


Figure A-110— FTIR results of C3 Asphaltenes fraction

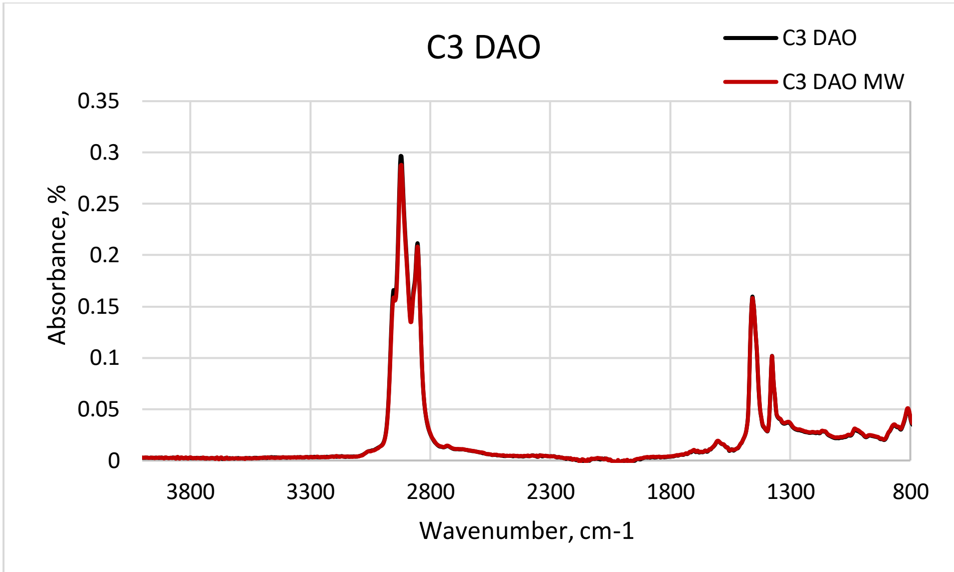


Figure A-111— FTIR results of C3 DAO

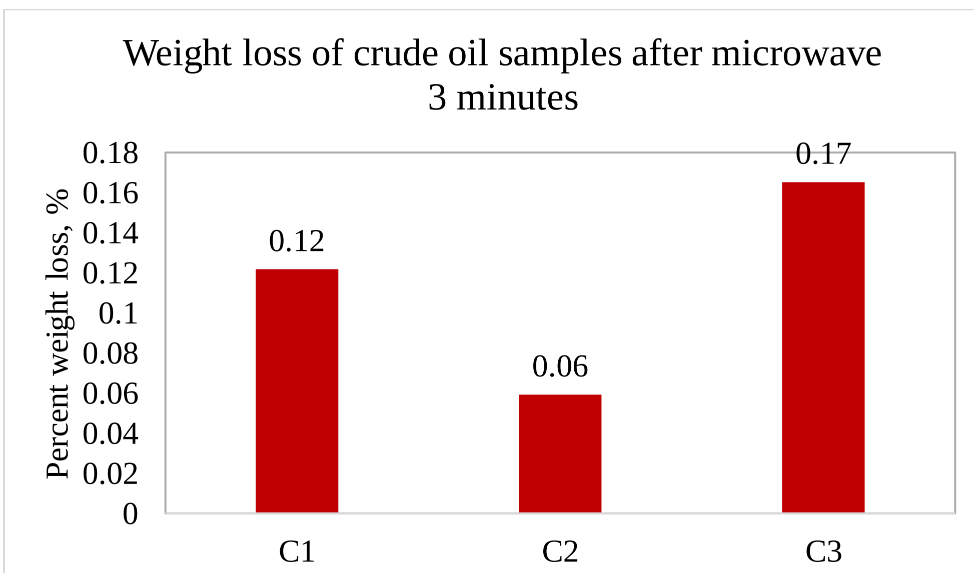


Figure A-112— Percent weight loss of crude oil samples after microwave of 3 minutes