Analysis of Polychlorinated Biphenyls in Electric Transformer Oil Using Gas Chromatography With Electron Capture Detector.

Vivek Mann

ANALYSIS OF POLYCHLORINATED BIPHENYLS IN ELECTRIC TRANSFORMER OIL USING GAS CHROMATOGRAPHY WITH ELECTRON CAPTURE DETECTOR

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Vivek Mann, Ph.D.

Texas Southern University

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Approved by

Dr. Mahmoud Saleh
Chairperson, Thesis Committee

Dr. Gregory Maddox
Dean, The Graduate School

Approved by

Dr. Mahmoud Saleh	12/16/2021
Chairperson, Thesis Committee	Date
Dr. Bobby Wilson	12/16/2021
Committee Member	Date
Dr. Alamelu Sundaresan	12/16/2021
Committee Member	Date
Dr. Daryl Wilkerson	12/16/2021
Committee Member	Date

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Professor Mahmoud A. Saleh, Ph.D., Advisor

Polychlorinated biphenyls (PCB's) are a group of synthetic chemicals which are environmentally insistent that were once used as coolants and lubricants in paints, heat transfer fluids, transformers, capacitors, caulking materials and other electrical materials owning to their property of good insulators. PCBs are persistent organic pollutants since they are persistent, resistant to biodegradation, bioaccumulate and have shown to cause a variety of deleterious effects on human health and the environment. Due to this the manufacturing of PCBs was banned in the United States in 1977. Although, production of PCBs has reportedly stopped, the potential or actual release of PCBs into the environment has not, as significant number of existing PCBs continue in use (electrical transformers and capacitors) or in storage. The Stockholm Convention on persistent organic pollutants (POPS) has already banned any further manufacture of nine transformer oil samples collected randomly from different sites. A standard quantitative analysis calibration curve

was created using clean transformer oil spiked with 5 different concentration and using decachlorobiphenyl as internal standard. Selective ion GC with electron capture device was performed on each sample, and the amount of PCBs were estimated using the calibration curve.

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LIST OF ABBREVIATIONS

ECD	Electron Capture Device
EPA	Environmental Protection Agency
CAS	Chemical Abstract Service Registry Number
GC	Gas Chromatograph
IUPAC	International Union of Pure and Applied Chemistry
PCB	Polychlorinated Biphely
TEF	Toxicity Equivalent Factor
WHO	World Health Organization

VITA

2006 …………………………………………	M.D. Medicine Russian State Medical University
2010 ……………………………………….	Master of Healthcare Administration University of Houston, Clear Lake Houston, Texas
2017 ……………………………………….	Ph.D., Environmental Toxicology Texas Southern University Houston, Texas
2017-2021……………………………………	Adjunct Faculty Department of Biology Texas Southern University Houston, Texas
Major Field…………………………………	Chemistry

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CHAPTER 1

INTRODUCTION

Polychlorinated Biphenyls often known as PCB's are a group of manufactured organic chemicals consisting of carbon, hydrogen, and chlorine atoms. The physical and chemical properties of PCBs are dependent upon the amount of chlorine atoms and their position in a PCB molecule. PCBs are tasteless or odorless and can range from an oil to a waxy solid. PCBs are a group of aromatic compounds where some or all hydrogen atoms are attached to the biphenyl ring are substituted by chlorine atoms (m + n =1-10). The general chemical formula is $C_{12}H_{(10\text{-}m\text{-}n)}\ Cl_{(m+n)}$, where (m+n) is the number of chlorine atoms on the two rings (Figure1). There are theoretically 209 individual PCB compounds (congeners, depending on the position and number of chlorine atoms (Ballschmiter and Zell 1980) The carbon atoms are numbered 1 to 6 on one ring and 1' to 6' on the other. Although positions 2,2'6, and 6' are called "*ortho*", positions 3,3'5, and 5' are named "*meta*" and positions 4 and 4' are called "*para*".

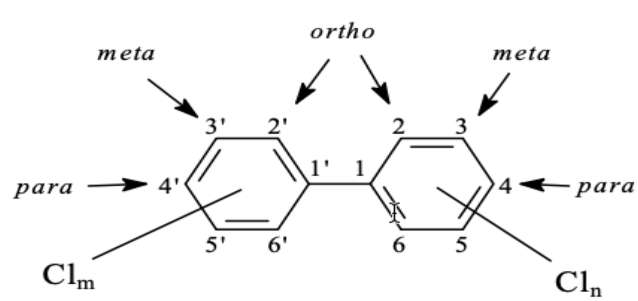

Figure 1: Chemical Structure of PCBs and the IUPAC Numbering System (Courtesy: IARC, 2016)

The two aromatic rings in the biphenyl molecule, can rotate about the connecting single 1,1′- bond (Figure 1). Like all molecules, there is a low-energy preferred conformation. With PCBs, this conformation is reliant on the degree of chlorine substitution, since chlorine is larger than hydrogen and creates more steric hindrance to the rotation (Erickson, 2001). The two extreme conceptual configurations are "planar" or "coplanar," in which the two benzene rings are in the same plane, and "non-planar" in which the benzene rings are at a 90° angle to each other (Faroon et al., 2000). The likelihood of acquiring a planar configuration is essentially determined by the number of substitutions in the *ortho* positions (2,2′,6,6′): the benzene rings of non-*ortho* substituted PCBs as well as mono-*ortho* substituted PCBs can procure a planar configuration and are referred to as "planar" or "coplanar" congeners (Erickson, 1997). The substitution of hydrogen atoms in the *ortho* positions with larger chlorine atoms forces the aromatic rings to rotate out of the planar configuration, such structures are referred to as "non-planar" or "non-co- planar" congeners (Schulte and Malisch, 1983)

There are twelve "dioxin like" congeners display all descriptors: PCB-77, PCB-81, PCB-105, PCB-114, PCB-118, PCB-123, PCB-126, PCB-156, PCB-157, PCB-167, PCB-169, and PCB-189, have been allocated toxicity equivalency factors (TEFs, assigned by WHO in 1998 and revised in 2005) (Liu et al., 2009).

PCBs were produced nation-wide from 1929 until fabrication was banned in 1979. First manufactured by Monsanto (the only American company to manufacture PCBs) in 1929, PCBs were quickly acclaimed as an industrial breakthrough (EPA 2021). These chlorinated oils have a low degree of reactivity. They are not flammable, have high electrical resistance, good insulating properties and are very stable even when exposed to heat and pressure (Balescu, 1975). All in all, they seemed to be the perfect oil for use in dielectric fluids, and as insulators for transformers and capacitors (UNEP, 2003). PCBs have an array of toxicity and can range from thin, light-colored liquids to yellow or black waxy solids (UNEP Chemical, 1999). Because of their properties such as non-combustibility, chemical stability, high boiling point, and electrical insulating properties (Safe, 1998), PCBs were widely employed in various industrial and commercial applications including: Electrical, heat transfer and hydraulic equipment, plasticizers in paints, rubber products, dyes, carbonless copy paper and other industrial applications.

Monsanto Corporation, the major U.S. producer of PCBs from 1930 to 1977, merchandised compositions of PCBs under the brand name Aroclor (Markowitz, 2018). The Aroclors are identified by a four-digit numbering code in which the first two digits indicate the type of mixture, and the last two digits indicate the approximate chlorine content by weight percent. Thus, Aroclor 1242 is a chlorinated biphenyl mixture of varying amounts of mono- through heptachlorinated homologs with an average chlorine content of 42%. The exception to this code is Aroclor 1016, which contains mono- through hexachlorinated homologs with an average chlorine content of 41% (Hutzinger et al., 1974). The chemical identity of the Aroclors is summarized in Table 1. The identity of the 209 PCB congeners is shown in Table 1. The congeners are arranged in ascending numerical order using a numbering system developed by Ballschmiter and Zell (1980) that follow the IUPAC rules of substituent characterization in biphenyls. The resulting PCB numbers, also referred to as congener, IUPAC, or BZ numbers, are widely used for identifying individual congeners.

CHAPTER 2

LITERATURE REVIEW

PCBs are no longer commercially produced in the United States, even then they may be present in products and materials produced before the 1979 PCB ban (EPA 2010). Products that may contain PCBs include transformers and capacitors, electrical equipment including voltage regulators, bushings, and electromagnets, motor oil, fluorescent light ballasts, cable insulation, thermal insulation material including fiberglass, felt, foam, and cork, adhesives and tapes, oil-based paint, caulking, floor finish etc., (Green facts, 2021).

These products were made up PCBs chemical mixtures containing a variety of individual chlorinated biphenyl components known as congeners. The most common brand name used for commercial PCB mixtures in the United States is Arochlor. In present day scenario, PCBs can still be discharge into the surroundings due to badly managed hazardous waste sites containing PCBs, inappropriate dumping of PCB wastes, leaks or releases from electrical transformers containing PCBs, dumping of PCB-containing merchandise into landfills not devised to handle high-risk waste and burning some wastes in municipal and industrial incinerators (Te et al, 2020).

PCBs do not disintegrate easily once in the habitat. They can persist for extended periods of time disseminating between air, water, and soil. They can travel long stretches and have come across in areas far from where they were discharged into the environment.

Consequently, they are found all over the world. PCBs can concentrate in the leaves of plants and food crops. They are also absorbed into the bodies of small organisms and fish. Consequently, people who ingest fish may be exposed to PCBs that have bioaccumulated in the fish they are ingesting.

PCB Congeners

A PCB congener is any single, unique well-defined chemical compound in the PCB category. The name of a congener specifies the total number of chlorine substituents, and the position of each chlorine (Teresa et al 2001). For example: 4,4'-Dichlorobiphenyl is a congener comprising the biphenyl structure with two chlorine substituents - one on each of the #4 carbons of the two rings. In 1980, a numbering system was developed which assigned a sequential number to each of the 209 PCB congeners.

Table 1: List of PCB Congeners with Descriptor, CASRN, Congener Number, IUPAC Name and Category

Descriptor*	CASRN	Congener Number	IUPAC Name	Type
	1336-36-3		Polychlorinated biphenyl (PCB)	Category
CP1_---_--_-	2051-60-7	1	2-Chlorobiphenyl	Congener
CP0_---_--_-	2051-61-8	2	3-Chlorobiphenyl	Congener
CP0_---_--_-	2051-62-9	3	4-Chlorobiphenyl	Congener
---_---_--_-	13029-08-8	4	2,2'-Dichlorobiphenyl	Congener
CP1_---_--_-	16605-91-7	5	2,3-Dichlorobiphenyl	Congener
CP1_---_--_-	25569-80-6	6	2,3'-Dichlorobiphenyl	Congener
CP1_---_--_-	33284-50-3	7	2,4-Dichlorobiphenyl	Congener
CP1_---_--_-	34883-43-7	8	2,4'-Dichlorobiphenyl	Congener
CP1_---_--_-	34883-39-1	9	2,5-Dichlorobiphenyl	Congener

---_---_--_-	33146-45-1	10	2,6-Dichlorobiphenyl	Congener
CP0_---_--_2M	2050-67-1	11	3,3'-Dichlorobiphenyl	Congener
CP0_---_--_-	2974-92-7	12	3,4-Dichlorobiphenyl	Congener
CP0_---_--_-	2974-90-5	13	3,4'-Dichlorobiphenyl	Congener
CP0_---_--_2M	34883-41-5	14	3,5-Dichlorobiphenyl	Congener
CP0_---_PP_-	2050-68-2	15	4,4'-Dichlorobiphenyl	Congener
---_---_--_-	38444-78-9	16	2,2',3-Trichlorobiphenyl	Congener
---_---_--_-	37680-66-3	17	2,2',4-Trichlorobiphenyl	Congener
---_---_--_-	37680-65-2	18	2,2',5-Trichlorobiphenyl	Congener
---_---_--_-	38444-73-4	19	2,2',6-Trichlorobiphenyl	Congener
CP1_---_--_2M	38444-84-7	20	2,3,3'-Trichlorobiphenyl	Congener
CP1_---_--_-	55702-46-0	21	2,3,4-Trichlorobiphenyl	Congener
CP1_---_--_-	38444-85-8	22	2,3,4'-Trichlorobiphenyl	Congener
CP1_---_--_2M	55720-44-0	23	2,3,5-Trichlorobiphenyl	Congener
---_---_--_-	55702-45-9	24	2,3,6-Trichlorobiphenyl	Congener
CP1_---_--_-	55712-37-3	25	2,3',4-Trichlorobiphenyl	Congener
CP1_---_--_2M	38444-81-4	26	2,3',5-Trichlorobiphenyl	Congener
---_---_--_-	38444-76-7	27	2,3',6-Trichlorobiphenyl	Congener
CP1_---_PP_-	7012-37-5	28	2,4,4'-Trichlorobiphenyl	Congener
CP1_---_--_-	15862-07-4	29	2,4,5-Trichlorobiphenyl	Congener
---_---_--_-	35693-92-6	30	2,4,6-Trichlorobiphenyl	Congener
CP1_---_--_-	16606-02-3	31	2,4',5-Trichlorobiphenyl	Congener
---_---_--_-	38444-77-8	32	2,4',6-Trichlorobiphenyl	Congener
CP1_---_--_-	38444-86-9	33	2,3',4'-Trichlorobiphenyl	Congener
CP1_---_--_2M	37680-68-5	34	2,3',5'-Trichlorobiphenyl	Congener
CP0_---_--_2M	37680-69-6	35	3,3',4-Trichlorobiphenyl	Congener
CP0_---_--_2M	38444-87-0	36	3,3',5-Trichlorobiphenyl	Congener

CP0_---_PP_-	38444-90-5	37	3,4,4'-Trichlorobiphenyl	Congener
CP0_---_--_2M	53555-66-1	38	3,4,5-Trichlorobiphenyl	Congener
CP0_---_--_2M	38444-88-1	39	3,4',5-Trichlorobiphenyl	Congener
---_4CL_--_2M	38444-93-8	40	2,2',3,3'-Tetrachlorobiphenyl	Congener
---_4CL_--_-	52663-59-9	41	2,2',3,4-Tetrachlorobiphenyl	Congener
---_4CL_--_-	36559-22-5	42	2,2',3,4'-Tetrachlorobiphenyl	Congener
---_4CL_--_2M	70362-46-8	43	2,2',3,5-Tetrachlorobiphenyl	Congener
---_4CL_--_2M	41464-39-5	44	2,2',3,5'-Tetrachlorobiphenyl	Congener
---_4CL_--_-	70362-45-7	45	2,2',3,6-Tetrachlorobiphenyl	Congener
---_4CL_--_-	41464-47-5	46	2,2',3,6'-Tetrachlorobiphenyl	Congener
---_4CL_PP_-	2437-79-8	47	2,2',4,4'-Tetrachlorobiphenyl	Congener
---_4CL_--_-	70362-47-9	48	2,2',4,5-Tetrachlorobiphenyl	Congener
---_4CL_--_-	41464-40-8	49	2,2',4,5'-Tetrachlorobiphenyl	Congener
---_4CL_--_-	62796-65-0	50	2,2',4,6-Tetrachlorobiphenyl	Congener
---_4CL_--_-	68194-04-7	51	2,2',4,6'-Tetrachlorobiphenyl	Congener
---_4CL_--_2M	35693-99-3	52	2,2',5,5'-Tetrachlorobiphenyl	Congener
---_4CL_--_-	41464-41-9	53	2,2',5,6'-Tetrachlorobiphenyl	Congener
---_4CL_--_-	15968-05-5	54	2,2',6,6'-Tetrachlorobiphenyl	Congener
CP1_4CL_--_2M	74338-24-2	55	2,3,3',4-Tetrachlorobiphenyl	Congener
CP1_4CL_--_2M	41464-43-1	56	2,3,3',4'-Tetrachlorobiphenyl	Congener
CP1_4CL_--_2M	70424-67-8	57	2,3,3',5-Tetrachlorobiphenyl	Congener
CP1_4CL_--_2M	41464-49-7	58	2,3,3',5'-Tetrachlorobiphenyl	Congener
---_4CL_--_2M	74472-33-6	59	2,3,3',6-Tetrachlorobiphenyl	Congener
CP1_4CL_PP_-	33025-41-1	60	2,3,4,4'-Tetrachlorobiphenyl	Congener
CP1_4CL_--_2M	33284-53-6	61	2,3,4,5-Tetrachlorobiphenyl	Congener

---_4CL_--_-	54230-22-7	62	2,3,4,6-Tetrachlorobiphenyl	Congener
CP1_4CL_--_2M	74472-34-7	63	2,3,4',5-Tetrachlorobiphenyl	Congener
---_4CL_--_-	52663-58-8	64	2,3,4',6-Tetrachlorobiphenyl	Congener
---_4CL_--_2M	33284-54-7	65	2,3,5,6-Tetrachlorobiphenyl	Congener
CP1_4CL_PP_-	32598-10-0	66	2,3',4,4'-Tetrachlorobiphenyl	Congener
CP1_4CL_--_2M	73575-53-8	67	2,3',4,5-Tetrachlorobiphenyl	Congener
CP1_4CL_--_2M	73575-52-7	68	2,3',4,5'-Tetrachlorobiphenyl	Congener
---_4CL_--_-	60233-24-1	69	2,3',4,6-Tetrachlorobiphenyl	Congener
CP1_4CL_--_2M	32598-11-1	70	2,3',4',5-Tetrachlorobiphenyl	Congener
---_4CL_--_-	41464-46-4	71	2,3',4',6-Tetrachlorobiphenyl	Congener
CP1_4CL_--_2M	41464-42-0	72	2,3',5,5'-Tetrachlorobiphenyl	Congener
---_4CL_--_2M	74338-23-1	73	2,3',5',6-Tetrachlorobiphenyl	Congener
CP1_4CL_PP_-	32690-93-0	74	2,4,4',5-Tetrachlorobiphenyl	Congener
---_4CL_PP_-	32598-12-2	75	2,4,4',6-Tetrachlorobiphenyl	Congener
CP1_4CL_--_2M	70362-48-0	76	2,3',4',5'-Tetrachlorobiphenyl	Congener
CP0_4CL_PP_2M	32598-13-3	77	3,3',4,4'-Tetrachlorobiphenyl	Congener
CP0_4CL_--_2M	70362-49-1	78	3,3',4,5-Tetrachlorobiphenyl	Congener
CP0_4CL_--_2M	41464-48-6	79	3,3',4,5'-Tetrachlorobiphenyl	Congener
CP0_4CL_--_2M	33284-52-5	80	3,3',5,5'-Tetrachlorobiphenyl	Congener
CP0_4CL_PP_2M	70362-50-4	81	3,4,4',5-Tetrachlorobiphenyl	Congener
---_4CL_--_2M	52663-62-4	82	2,2',3,3',4-Pentachlorobiphenyl	Congener
---_4CL_--_2M	60145-20-2	83	2,2',3,3',5-Pentachlorobiphenyl	Congener
---_4CL_--_2M	52663-60-2	84	2,2',3,3',6-Pentachlorobiphenyl	Congener
---_4CL_PP_-	65510-45-4	85	2,2',3,4,4'-Pentachlorobiphenyl	Congener
---_4CL_--_2M	55312-69-1	86	2,2',3,4,5-Pentachlorobiphenyl	Congener

---_4CL_--_2M	38380-02-8	87	2,2',3,4,5'-Pentachlorobiphenyl	Congener
---_4CL_--_-	55215-17-3	88	2,2',3,4,6-Pentachlorobiphenyl	Congener
---_4CL_--_-	73575-57-2	89	2,2',3,4,6'-Pentachlorobiphenyl	Congener
---_4CL_--_2M	68194-07-0	90	2,2',3,4',5-Pentachlorobiphenyl	Congener
---_4CL_--_-	68194-05-8	91	2,2',3,4',6-Pentachlorobiphenyl	Congener
---_4CL_--_2M	52663-61-3	92	2,2',3,5,5'-Pentachlorobiphenyl	Congener
---_4CL_--_2M	73575-56-1	93	2,2',3,5,6-Pentachlorobiphenyl	Congener
---_4CL_--_2M	73575-55-0	94	2,2',3,5,6'-Pentachlorobiphenyl	Congener
---_4CL_--_2M	38379-99-6	95	2,2',3,5',6-Pentachlorobiphenyl	Congener
---_4CL_--_-	73575-54-9	96	2,2',3,6,6'-Pentachlorobiphenyl	Congener
---_4CL_--_2M	41464-51-1	97	2,2',3,4',5'-Pentachlorobiphenyl	Congener
---_4CL_--_-	60233-25-2	98	2,2',3,4',6'-Pentachlorobiphenyl	Congener
---_4CL_PP_-	38380-01-7	99	2,2',4,4',5-Pentachlorobiphenyl	Congener
---_4CL_PP_-	39485-83-1	100	2,2',4,4',6-Pentachlorobiphenyl	Congener
---_4CL_--_2M	37680-73-2	101	2,2',4,5,5'-Pentachlorobiphenyl	Congener
---_4CL_--_-	68194-06-9	102	2,2',4,5,6'-Pentachlorobiphenyl	Congener
---_4CL_--_-	60145-21-3	103	2,2',4,5',6-Pentachlorobiphenyl	Congener
---_4CL_--_-	56558-16-8	104	2,2',4,6,6'-Pentachlorobiphenyl	Congener
CP1_4CL_PP_2M	32598-14-4	105	2,3,3',4,4'-Pentachlorobiphenyl	Congener
CP1_4CL_--_2M	70424-69-0	106	2,3,3',4,5-Pentachlorobiphenyl	Congener
CP1_4CL_--_2M	70424-68-9	107	2,3,3',4',5-Pentachlorobiphenyl	Congener
CP1_4CL_--_2M	70362-41-3	108	2,3,3',4,5'-Pentachlorobiphenyl	Congener
---_4CL_--_2M	74472-35-8	109	2,3,3',4,6-Pentachlorobiphenyl	Congener
---_4CL_--_2M	38380-03-9	110	2,3,3',4',6-Pentachlorobiphenyl	Congener
CP1_4CL_--_2M	39635-32-0	111	2,3,3',5,5'-Pentachlorobiphenyl	Congener

---_4CL_--_2M	74472-36-9	112	2,3,3',5,6-Pentachlorobiphenyl	Congener
---_4CL_--_2M	68194-10-5	113	2,3,3',5',6-Pentachlorobiphenyl	Congener
CP1_4CL_PP_2M	74472-37-0	114	2,3,4,4',5-Pentachlorobiphenyl	Congener
---_4CL_PP_-	74472-38-1	115	2,3,4,4',6-Pentachlorobiphenyl	Congener
---_4CL_--_2M	18259-05-7	116	2,3,4,5,6-Pentachlorobiphenyl	Congener
---_4CL_--_2M	68194-11-6	117	2,3,4',5,6-Pentachlorobiphenyl	Congener
CP1_4CL_PP_2M	31508-00-6	118	2,3',4,4',5-Pentachlorobiphenyl	Congener
---_4CL_PP_-	56558-17-9	119	2,3',4,4',6-Pentachlorobiphenyl	Congener
CP1_4CL_--_2M	68194-12-7	120	2,3',4,5,5'-Pentachlorobiphenyl	Congener
---_4CL_--_2M	56558-18-0	121	2,3',4,5',6-Pentachlorobiphenyl	Congener
CP1_4CL_--_2M	76842-07-4	122	2,3,3',4',5'-Pentachlorobiphenyl	Congener
CP1_4CL_PP_2M	65510-44-3	123	2,3',4,4',5'-Pentachlorobiphenyl	Congener
CP1_4CL_--_2M	70424-70-3	124	2,3',4',5,5'-Pentachlorobiphenyl	Congener
---_4CL_--_2M	74472-39-2	125	2,3',4',5',6-Pentachlorobiphenyl	Congener
CP0_4CL_PP_2M	57465-28-8	126	3,3',4,4',5-Pentachlorobiphenyl	Congener
CP0_4CL_--_2M	39635-33-1	127	3,3',4,5,5'-Pentachlorobiphenyl	Congener
---_4CL_PP_2M	38380-07-3	128	2,2',3,3',4,4'-Hexachlorobiphenyl	Congener
---_4CL_--_2M	55215-18-4	129	2,2',3,3',4,5-Hexachlorobiphenyl	Congener
---_4CL_--_2M	52663-66-8	130	2,2',3,3',4,5'-Hexachlorobiphenyl	Congener
---_4CL_--_2M	61798-70-7	131	2,2',3,3',4,6-Hexachlorobiphenyl	Congener
---_4CL_--_2M	38380-05-1	132	2,2',3,3',4,6'-Hexachlorobiphenyl	Congener
---_4CL_--_2M	35694-04-3	133	2,2',3,3',5,5'-Hexachlorobiphenyl	Congener
---_4CL_--_2M	52704-70-8	134	2,2',3,3',5,6-Hexachlorobiphenyl	Congener
---_4CL_--_2M	52744-13-5	135	2,2',3,3',5,6'-Hexachlorobiphenyl	Congener
---_4CL_--_2M	38411-22-2	136	2,2',3,3',6,6'-Hexachlorobiphenyl	Congener

---_4CL_PP_2M	35694-06-5	137	2,2',3,4,4',5-Hexachlorobiphenyl	Congener
---_4CL_PP_2M	35065-28-2	138	2,2',3,4,4',5'-Hexachlorobiphenyl	Congener
---_4CL_PP_-	56030-56-9	139	2,2',3,4,4',6-Hexachlorobiphenyl	Congener
---_4CL_PP_-	59291-64-4	140	2,2',3,4,4',6'-Hexachlorobiphenyl	Congener
---_4CL_--_2M	52712-04-6	141	2,2',3,4,5,5'-Hexachlorobiphenyl	Congener
---_4CL_--_2M	41411-61-4	142	2,2',3,4,5,6-Hexachlorobiphenyl	Congener
---_4CL_--_2M	68194-15-0	143	2,2',3,4,5,6'-Hexachlorobiphenyl	Congener
---_4CL_--_2M	68194-14-9	144	2,2',3,4,5',6-Hexachlorobiphenyl	Congener
---_4CL_--_-	74472-40-5	145	2,2',3,4,6,6'-Hexachlorobiphenyl	Congener
---_4CL_--_2M	51908-16-8	146	2,2',3,4',5,5'-Hexachlorobiphenyl	Congener
---_4CL_--_2M	68194-13-8	147	2,2',3,4',5,6-Hexachlorobiphenyl	Congener
---_4CL_--_2M	74472-41-6	148	2,2',3,4',5,6'-Hexachlorobiphenyl	Congener
---_4CL_--_2M	38380-04-0	149	2,2',3,4',5',6-Hexachlorobiphenyl	Congener
---_4CL_--_-	68194-08-1	150	2,2',3,4',6,6'-Hexachlorobiphenyl	Congener
---_4CL_--_2M	52663-63-5	151	2,2',3,5,5',6-Hexachlorobiphenyl	Congener
---_4CL_--_2M	68194-09-2	152	2,2',3,5,6,6'-Hexachlorobiphenyl	Congener
---_4CL_PP_2M	35065-27-1	153	2,2',4,4',5,5'-Hexachlorobiphenyl	Congener
---_4CL_PP_-	60145-22-4	154	2,2',4,4',5,6'-Hexachlorobiphenyl	Congener
---_4CL_PP_-	33979-03-2	155	2,2',4,4',6,6'-Hexachlorobiphenyl	Congener
CP1_4CL_PP_2M	38380-08-4	156	2,3,3',4,4',5-Hexachlorobiphenyl	Congener
CP1_4CL_PP_2M	69782-90-7	157	2,3,3',4,4',5'-Hexachlorobiphenyl	Congener
---_4CL_PP_2M	74472-42-7	158	2,3,3',4,4',6-Hexachlorobiphenyl	Congener
CP1_4CL_--_2M	39635-35-3	159	2,3,3',4,5,5'-Hexachlorobiphenyl	Congener
---_4CL_--_2M	41411-62-5	160	2,3,3',4,5,6-Hexachlorobiphenyl	Congener
---_4CL_--_2M	74472-43-8	161	2,3,3',4,5',6-Hexachlorobiphenyl	Congener

CP1_4CL_--_2M	39635-34-2	162	2,3,3',4',5,5'-Hexachlorobiphenyl	Congener
---_4CL_--_2M	74472-44-9	163	2,3,3',4',5,6-Hexachlorobiphenyl	Congener
---_4CL_--_2M	74472-45-0	164	2,3,3',4',5',6-Hexachlorobiphenyl	Congener
---_4CL_--_2M	74472-46-1	165	2,3,3',5,5',6-Hexachlorobiphenyl	Congener
---_4CL_PP_2M	41411-63-6	166	2,3,4,4',5,6-Hexachlorobiphenyl	Congener
CP1_4CL_PP_2M	52663-72-6	167	2,3',4,4',5,5'-Hexachlorobiphenyl	Congener
---_4CL_PP_2M	59291-65-5	168	2,3',4,4',5',6-Hexachlorobiphenyl	Congener
CP0_4CL_PP_2M	32774-16-6	169	3,3',4,4',5,5'-Hexachlorobiphenyl	Congener
---_4CL_PP_2M	35065-30-6	170	2,2',3,3',4,4',5-Heptachlorobiphenyl	Congener
---_4CL_PP_2M	52663-71-5	171	2,2',3,3',4,4',6-Heptachlorobiphenyl	Congener
---_4CL_--_2M	52663-74-8	172	2,2',3,3',4,5,5'-Heptachlorobiphenyl	Congener
---_4CL_--_2M	68194-16-1	173	2,2',3,3',4,5,6-Heptachlorobiphenyl	Congener
---_4CL_--_2M	38411-25-5	174	2,2',3,3',4,5,6'-Heptachlorobiphenyl	Congener
---_4CL_--_2M	40186-70-7	175	2,2',3,3',4,5',6-Heptachlorobiphenyl	Congener
---_4CL_--_2M	52663-65-7	176	2,2',3,3',4,6,6'-Heptachlorobiphenyl	Congener
---_4CL_--_2M	52663-70-4	177	2,2',3,3',4,5',6'-Heptachlorobiphenyl	Congener
---_4CL_--_2M	52663-67-9	178	2,2',3,3',5,5',6-Heptachlorobiphenyl	Congener
---_4CL_--_2M	52663-64-6	179	2,2',3,3',5,6,6'-Heptachlorobiphenyl	Congener
---_4CL_PP_2M	35065-29-3	180	2,2',3,4,4',5,5'-Heptachlorobiphenyl	Congener
---_4CL_PP_2M	74472-47-2	181	2,2',3,4,4',5,6-Heptachlorobiphenyl	Congener
---_4CL_PP_2M	60145-23-5	182	2,2',3,4,4',5,6'-Heptachlorobiphenyl	Congener
---_4CL_PP_2M	52663-69-1	183	2,2',3,4,4',5',6-Heptachlorobiphenyl	Congener
---_4CL_PP_-	74472-48-3	184	2,2',3,4,4',6,6'-Heptachlorobiphenyl	Congener
---_4CL_--_2M	52712-05-7	185	2,2',3,4,5,5',6-Heptachlorobiphenyl	Congener
---_4CL_--_2M	74472-49-4	186	2,2',3,4,5,6,6'-Heptachlorobiphenyl	Congener

---_4CL_--_2M	52663-68-0	187	2,2',3,4',5,5',6-Heptachlorobiphenyl	Congener
---_4CL_--_2M	74487-85-7	188	2,2',3,4',5,6,6'-Heptachlorobiphenyl	Congener
CP1_4CL_PP_2M	39635-31-9	189	2,3,3',4,4',5,5'-Heptachlorobiphenyl	Congener
---_4CL_PP_2M	41411-64-7	190	2,3,3',4,4',5,6-Heptachlorobiphenyl	Congener
---_4CL_PP_2M	74472-50-7	191	2,3,3',4,4',5',6-Heptachlorobiphenyl	Congener
---_4CL_--_2M	74472-51-8	192	2,3,3',4,5,5',6-Heptachlorobiphenyl	Congener
---_4CL_--_2M	69782-91-8	193	2,3,3',4',5,5',6-Heptachlorobiphenyl	Congener
---_4CL_PP_2M	35694-08-7	194	2,2',3,3',4,4',5,5'-Octachlorobiphenyl	Congener
---_4CL_PP_2M	52663-78-2	195	2,2',3,3',4,4',5,6-Octachlorobiphenyl	Congener
---_4CL_PP_2M	42740-50-1	196	2,2',3,3',4,4',5,6'-Octachlorobiphenyl	Congener
---_4CL_PP_2M	33091-17-7	197	2,2',3,3',4,4',6,6'-Octachlorobiphenyl	Congener
---_4CL_--_2M	68194-17-2	198	2,2',3,3',4,5,5',6-Octachlorobiphenyl	Congener
---_4CL_--_2M	52663-75-9	199	2,2',3,3',4,5,5',6'-Octachlorobiphenyl	Congener
---_4CL_--_2M	52663-73-7	200	2,2',3,3',4,5,6,6'-Octachlorobiphenyl	Congener
---_4CL_--_2M	40186-71-8	201	2,2',3,3',4,5',6,6'-Octachlorobiphenyl	Congener
---_4CL_--_2M	2136-99-4	202	2,2',3,3',5,5',6,6'-Octachlorobiphenyl	Congener
---_4CL_PP_2M	52663-76-0	203	2,2',3,4,4',5,5',6-Octachlorobiphenyl	Congener
---_4CL_PP_2M	74472-52-9	204	2,2',3,4,4',5,6,6'-Octachlorobiphenyl	Congener
---_4CL_PP_2M	74472-53-0	205	2,3,3',4,4',5,5',6-Octachlorobiphenyl	Congener
---_4CL_PP_2M	40186-72-9	206	2,2',3,3',4,4',5,5',6-Nonachlorobiphenyl	Congener
---_4CL_PP_2M	52663-79-3	207	2,2',3,3',4,4',5,6,6'-Nonachlorobiphenyl	Congener
---_4CL_--_2M	52663-77-1	208	2,2',3,3',4,5,5',6,6'-Nonachlorobiphenyl	Congener
---_---_--_-	2051-24-3	209	Decachlorobiphenyl	Congener

Table 2: Descriptors of PCB Congeners

Descriptors	
CP0/CP1	These 68 co-planar congeners include 20 with chlorine substitution at none (CP0, nonortho) and 48 with chlorine substitution at only one (CP1, mono-ortho) of the 2, 2', 6, or 6' positions.
4CL	These 169 congeners have a total of four or more chlorine substituents (regardless of position).
PP	These 54 congeners have both para positions (4 and 4') chlorinated.
2M	These 140 congeners have two or more of the meta positions (3, 3', 5, and 5') chlorinated.

PCB Homologs

Homologs are subsets of PCB congeners that have equal numbers of chlorine substituents. For example, the tetrachlorobiphenyls are all PCB congeners with exactly 4 chlorine substituents that can be in any arrangement.

Table 3: List of PCB Homologs with CASRN and IUPAC Name

CASRN	IUPAC Name	Type
27323-18-8	Monochlorobiphenyl	Homolog
25512-42-9	Dichlorobiphenyl	Homolog
25323-68-6	Trichlorobiphenyl	Homolog
26914-33-0	Tetrachlorobiphenyl	Homolog
25429-29-2	Pentachlorobiphenyl	Homolog
26601-64-9	Hexachlorobiphenyl	Homolog
28655-71-2	Heptachlorobiphenyl	Homolog
55722-26-4	Octachlorobiphenyl	Homolog
53742-07-7	Nonachlorobiphenyl	Homolog

PCB Mixtures

In general, PCBs were manufactured as a mixture of individual PCB congeners. These mixtures were created by adding incrementally more chlorine to batches of biphenyl until a certain target percentage of chlorine by weight was achieved. Commercial mixtures with higher percentages of chlorine contained higher proportions of the more heavily chlorinated congeners, but all congeners could be expected to be present at some level in all mixtures. PCBs have been manufactured and sold under many names, the most common was the Aroclor series.

Aroclor

Aroclor is a PCB mixture produced from approximately 1930 to 1979. It is one of the most known trade names for PCB mixtures. There are many types of Aroclors, and each has a distinguishing suffix number that indicates the degree of chlorination. The numbering standard for the different Aroclors is as follows:

- The first two digits usually refer to the number of carbon atoms in the phenyl rings (for PCBs this is 12)
- The second two numbers indicate the percentage of chlorine by mass in the mixture. For example, the name Aroclor 1254 means that the mixture contains approximately 54% chlorine by weight.

Table 4: Types of PCB Mixtures (Aroclor) with CASRN, IUPAC Name

CASRN	IUPAC Name	Type
12674-11-2	Aroclor 1016	Mixture
147601-87-4	Aroclor 1210	Mixture
151820-27-8	Aroclor 1216	Mixture
11104-28-2	Aroclor 1221	Mixture
37234-40-5	Aroclor 1231	Mixture
11141-16-5	Aroclor 1232	Mixture
71328-89-7	Aroclor 1240	Mixture
53469-21-9	Aroclor 1242	Mixture
12672-29-6	Aroclor 1248	Mixture
165245-51-2	Aroclor 1250	Mixture
89577-78-6	Aroclor 1252	Mixture
11097-69-1	Aroclor 1254	Mixture
11096-82-5	Aroclor 1260	Mixture
37324-23-5	Aroclor 1262	Mixture
11100-14-4	Aroclor 1268	Mixture
12767-79-2	Aroclor (unspecified)	Mixture

Health Effects of PCBs

PCBs have been shown to cause an array of detrimental health effects. They have been demonstrated to generate malignancies in animals as well as many severe non-cancerous effects in animals, including deleterious effects on the immunity, reproductive system, nervous system, endocrine system, and other health effects. Human studies have validated potential carcinogenic and non-carcinogenic effects of PCBs. The various health outcomes of PCBs may be correlated. Modifications in one system may have major ramifications for the other systems of the body.

PCBs are one of the most widely studied environmental contaminants. Numerous animal and human studies have been performed to evaluate the carcinogenic possibilities of PCBs. EPA completed its first evaluation of PCB carcinogenicity in 1987. Due to limited data availability of Aroclor 1260, EPA later in 1996 completed a revaluation of PCB carcinogenicity. This revaluation showed the Agency's commitment to utilize latest science in assessing health effects of PCBs and concluding that PCBs are potential human carcinogens (EPA 1996).

EPA uses an approach that permits evaluation of the complete carcinogenicity database and allows the results of individual studies to be viewed in the context of all the other available studies. Studies in animals provide conclusive evidence that PCBs cause cancer. Studies in humans raise further concerns regarding the potential carcinogenicity of PCBs. Taken together, the data strongly suggest that PCBs are probable human carcinogens.

Non-Cancer Effects

EPA evaluates all the available data in determining the potential noncarcinogenic toxicity of environmental contaminants, including PCBs. Based on extensive human and animal studies, EPA established that PCBs have significant pernicious health effects. PCBs can disturb animal’s various systems including renal, immune, reproductive, nervous, and endocrine system. All these systems are complex and correlated and are tightly regulated. Consequently, it is not startling that PCBs can exert a myriad of deleterious health effects.

Persistent Organic Pollutants

PCBs are designated as persistent organic pollutants (POPs), because these are chemical substances that are persistent, bioaccumulate and adversely affect human health and the environment. They can be transported long distances and have been detected in the furthest corners of the globe, including places far from where they were manufactured and used.

While manufacture of PCBs has reportedly ceased, the potential or actual release of PCBs into the environment has not, since significant quantities of existing PCBs continue in use or in storage. Electrical transformers and capacitors are one such major source of PCBs. The likely extended period of continuing use and the persistence of PCBs once released into the environment together mean that PCBs could pose a threat for decades to come. While most of the 12 chemicals covered by the **Stockholm Convention** are subject to an immediate ban, in the case of PCBs existing equipment may be maintained in a way that prevents leaks until 2025 (while PCB-free replacements are being introduced). **The Stockholm Convention** on Persistent Organic Pollutants (POPS) recommends measurement of six indicator PCBs (PCB-28, PCB-52, PCB-101, PCB-138, PCB-153, and PCB-180) to characterize contamination by PCBs. These congeners were chosen because they are found at higher concentrations in the environment, in food, or in human fluids/tissues. Depending on country and context, different lists of varying numbers of congeners may be used, e.g. 36 congeners for the Centers for Disease Control and

Prevention, USA, or only PCB-138, PCB-153, and PCB-180 most frequently in epidemiological studies with human blood.

PCBs in Transformer Oil

Transformers are manufactured in a variety of shapes and sizes and are either dry-type or liquid-filled. In transformers containing dielectric fluid, the fluid also serves as a heat exchanger; heat from the windings is transferred to the casing. If the heat transfer capacity of a transformer casing is not sufficient, cooling tubes or fins can be added. These operate like a car radiator. Most larger transformers are characterized by these tubes or fins.

Transformers can be found in several locations i.e.: a. Indoors: mounted on a wall or column, in an electrical room or fenced enclosure, within fire-proof vaults, and in mines and underground vaults. b. Outdoors: on a roof, concrete pad, and utility pole. Indoor liquid-filled transformers must be nonflammable unless they are installed in a fireproof vault approved by the electrical inspection authorities. PCBs have very low flammability and were considered ideal for use in indoor liquid-filled transformers. Consequently, transformers of the type installed indoors prior to 1979, in locations other than fireproof vaults, often contain PCBs.

Summary of Chemical and Physical Properties of PCBs

Physical and chemical properties of PCBs are summarized in Table 5. A salient property of PCBs is their general inactivity; they resist both acids and alkalis and have thermal stability. This advantage made PCBs to be widely used in different application, including dielectric fluids in transformers and capacitors, heat transfer fluids, and lubricants (Afghan and Chau 1989). In general, PCBs are relatively insoluble in water, and the solubility decreases with increased chlorination. PCBs are also freely soluble in nonpolar organic solvents and biological lipids (EPA 1980b). PCBs are combustible liquids, and the products of combustion may be more hazardous than the material itself. By-products of combustion include hydrogen chloride, polychlorinated dibenzodioxins (PCDDs), and polychlorinated dibenzofurans (PCDFs) (NFPA 1994).

PCBs are practically fire resistant because of their high flash points (170–380 °C). They form vapors which are heavier than air but are not explosive. They have low electrical conductivity, high thermal conductivity, and high resistance to thermal degradation. Based on these properties, they have been used as dielectric isolators in electrical equipment. Like many organochlorine compounds, many of the congeners are highly persistent and accumulate within food chains. Investigations in many parts of the world have revealed widespread distribution of PCBs in the environment.

The universal distribution of PCBs throughout the world, suggests that PCBs are transported in air *(2)*. The ability of PCBs to co-distil, volatilize from landfills into the atmosphere (adsorption to aerosols with a particle size of < 0.05–20 μm), and resist degradation at low incinerating temperatures, makes atmospheric transport the primary mode of global distribution. In a study in the USA, 92% of the PCBs detected were in the vapour phase *(2)*. In a German study, congeners with a low degree of chlorination were dominant in filtered air, whereas those with a high degree dominated in aerosols and rainfall *(2)*.

Table 5: Summary of Physical-Chemical Properties of Some PCB Congeners

IUPAC no.	Congener	CAS no.	Molecular weight, MW g/mol	m.p. °C	b.p. °C	Fugacity ratio, F at 25°C*	Le Bas molar volume, V_M (cm^3/mol)
0	Biphenyl	92-52-4	154.207	68.93	256.1	0.371	184.6
1	2-	2051-60-7	188.652	34	274	0.816	205.5
2	3-	2051-61-8	188.652	16	284.5	1	205.5
3	4-	2051-62-9	188.652	78.8	292.9	0.297	205.5
4	2,2′-	13029-08-8	223.098	60.5		0.448	226.4
5	2,3-	16605-91-7	223.098	28		0.934	226.4
6	2,3′	25569–80–6	223.098				226.4
7	2,4-	33284-50-3	223.098	24.4		1	226.4
8	2,4′-	34883-43-7	223.098	43		0.666	226.4
9	2,5-	34883-39-1	223.098	22–23		1	226.4
10	2,6-	33146-45-1	223.098	35.5		0.789	226.4
11	3,3′-	2050-67-1	223.098	29	320	0.914	226.4
12	3,4-	2974-92-7	223.098	49	195–200	0.581	226.4
13	3,4′-	2974–90–5	223.098				226.4
14	3,5-	34883-41-5	223.098	31		0.873	226.4
15	4,4′-	2050-68-2	223.098	149.3	317	0.0603	226.4
16	2,2′,3-	38444-78-9	257.543	28		0.934	247.3
17	2,2′,4-	37680–66–3	257.543				247.3
18	2,2′,5-	37680-65-2	257.543	44		0.651	247.3
19	2,2′,6-	38444–73–4	257.543				247.3
20	2,3,3′-	38444-84-7	257.543				247.3
21	2,3,4-	55702-46-0	257.543	102		0.176	247.3
22	2,3,4′-	38444–85–8	257.543	73		0.338	247.3
23	2,3,5-	55720–44–0	257.543	41		0.697	247.3
24	2,3,6-	55702–45–9	257.543	49		0.581	247.3
25	2,3′,4-	55712–37–3	257.543				247.3
26	2,3′,5-	38444–81–4	257.543	40.5		0.705	247.3
27	2,3′,6-	38444–76–7	257.543				247.3
28	2,4,4′-	7012-37-5	257.543	57		0.485	247.3
29	2,4,5-	15862-07-4	257.543	78.5		0.299	247.3

continued

IUPAC no.	Congener	CAS no.	Molecular weight, MW g/mol	m.p. °C	b.p. °C	Fugacity ratio, F at 25°C*	Le Bas molar volume, V_M (cm³/mol)
30	2,4,6-	35693-92-6	257.543	62.5		0.429	247.3
31	2,4′,5-	16606-02-3	257.543	67		0.387	247.3
32	2,4′,6-	38444-77-8	257.543				247.3
33	2,3′,4′-	38444-86-9	257.543	60		0.454	247.3
34	2,3′,5′-	37680-68-5	257.543	58		0.474	247.3
35	3,3′,4-	37680-69-6	257.543	87		0.246	247.3
36	3,3′,5-	38444-87-0	257.543				247.3
37	3,4,4′-	38444-90-5	257.543	87		0.246	247.3
38	3,4,5-	53555-66-1	257.543				247.3
39	3,4′,5-	38444-88-1	257.543	88		0.241	247.3
40	2,2′,3,3′-	38444-93-8	291.988	121		0.114	268.2
41	2,2′,3,4-	52663-59-9	291.988				268.2
42	2,2′,3,4′-	36559-22-5	291.988	69		0.370	268.2
43	2,2′,3,5-	70362-46-8	291.988				268.2
44	2,2′,3,5′-	41464-39-5	291.988	47		0.608	268.2
45	2,2′,3,6-	70362-45-7	291.988				268.2
46	2,2′,3,6′-	41464-47-5	291.988				268.2
47	2,2′,4,4′-	2437-79-8	291.988	83		0.270	268.2
48	2,2′,4,5-	70362-47-9	291.988	65.9		0.397	268.2
49	2,2′,4, 5′-	41464-40-8	291.988	66.5		0.392	268.2
50	2,2′,4,6-	62796-65-8	291.988				268.2
51	2,2′,4,6′-	68194-04-7	291.988	66		0.396	268.2
52	2,2′,5,5′-	35693-99-3	291.988	87		0.246	268.2
53	2,2′,5,6′-	41464-41-9	291.988	104		0.168	268.2
54	2,2′,6,6′-	15968-05-5	291.988	198		0.0201	268.2
55	2,3,3′,4-	74338-24-2	291.988				268.2
56	2,3,3′,4′-	41464-43-1	291.988				268.2
57	2,3,3′,5-	70424-67-8	291.988				268.2
58	2,3,3′,5′-	41464-49-7	291.988				268.2
59	2,3,3′,6-	74472-33-6	291.988				268.2
60	2,3,4,4′-	33025-41-1	291.988	142		0.0711	268.2
61	2,3,4,5-	33284-53-6	291.988	92.2		0.219	268.2
62	2,3,4,6-	54230-23-7	291.988				268.2

continued

IUPAC no.	Congener	CAS no.	Molecular weight, MW g/mol	m.p. °C	b.p. °C	Fugacity ratio, F at 25°C*	Le Bas molar volume, V_M (cm^3/mol)
63	2,3,4′,5-	74472–34–7	291.988				268.2
64	2,3,4′,6-	52663–58–8	291.988				268.2
65	2,3,5,6-	33284-54-7	291.988	79		0.295	268.2
66	2,3′,4,4′-	32598-10-0	291.988	124		0.107	268.2
67	2,3′,4,5-	73575–53–8	291.988				268.2
68	2,3′,4,5′-	73575–52–7	291.988				268.2
69	2,3′,4,6-	60233–24–1	291.988				268.2
70	2,3′,4′,5-	32598-11-1	291.988	104		0.168	268.2
71	2,3′,4′,6-	41464–46–4	291.988				268.2
72	2,4′,5,5′-	41464–42–0	291.988				268.2
73	2,3′,5′,6-	74338–23–1	291.988				268.2
74	2,4,4′,5-	32690–93–0	291.988	125		0.104	268.2
75	2,4,4′,6-	32598-12-2	291.988				268.2
76	2,3′,4′,5′-	70362–48–0	291.988				268.2
77	3,3′,4,4′-	32598-13-3	291.988	180		0.0301	268.2
78	3,3′,4,5-	70362–49–1	291.988				268.2
79	3,3′,4,5′-	41464–48–6	291.988				268.2
80	3,3′,5,5′-	33284-52-5	291.988	164		0.0433	268.2
81	3,4,4′,5-	70362–50–4	291.988				268.2
82	2,2′,3,3′,4-	52663–62–4	326.433				289.1
83	2,2′,3,3′,5-	60145-20-2	326.433	65		0.405	289.1
84	2,2′,3,3′,6-	52663–60–2	326.433				289.1
85	2,2′,3,4,4′-	65510–45–4	326.433				289.1
86	2,2′,3,4,5-	55312-69-1	326.433	100		0.184	289.1
87	2,2′,3,4,5′-	38380-02-8	326.433	114		0.134	289.1
88	2,2′,3,4,6-	55215-17-3	326.433	100		0.184	289.1
89	2,2′,3,4,6′-	73575–57–2	326.433				289.1
90	2,2′,3,4′,5-	68194–07–0	326.433				289.1
91	2,2′,3,4′,6-	58194–05–8	326.433				289.1
92	2,2′,3,5,5′-	52663–61–3	326.433				289.1
93	2,2′,3,5,6-	73575–56–1	326.433				289.1
94	2,2′,3,5,6′-	73575–55–0	326.433				289.1
95	2,2′3,5,6-	38379-99-6	326.433	100		0.184	289.1
96	2,2′,3,6,6′-	73575–54–9	326.433				289.1
97	2,2′,3,4′,5′-	41464–51–1	326.433	82		0.276	289.1
98	2,2′,3,4′,6′-	60233–25–2	326.433				289.1
99	2,2′,4,4′,5-	38380-01-7	326.433				289.1

continued

IUPAC no.	Congener	CAS no.	Molecular weight, MW g/mol	m.p. °C	b.p. °C	Fugacity ratio, F at 25°C*	Le Bas molar volume, V_M (cm³/mol)
133	2,2′,3,3′,5,5′-	35694–04–3	360.878	129		0.0954	310.0
134	2,2′,3,3′,5,6-	52704-70-8	360.878	100		0.184	310.0
135	2,2′,3,3′,5,6′-	52744–13–5	360.878				310.0
136	2,2′,3,3′,6,6′-	38411-22-2	360.878	114.2		0.133	310.0
137	2,2′,3,4,4′,5-	35694–06–5	360.878	78		0.302	310.0
138	2,2′,3,4,4′,5′-	35065-28-2	360.878	80		0.289	310.0
139	2,2′,3,4,4′,6-	56030–56–9	360.878				310.0
140	2,2′,3,4,4′,6′-	59291–64–4	360.878				310.0
141	2,2,3,4,5,5′-	52712–04–6	360.878	85		0.258	310.0
142	2,2′,3,4,5,6-	41411–61–4	360.878	136		0.0815	310.0
143	2,2′,3,4,5,6′-	68194–15–0	360.878				310.0
144	2,2′,3,4,5′,6-	68194–14–9	360.878				310.0
145	2,2′,3,4,6,6′-	74472–40–5	360.878				310.0
146	2,2′,3,4′,5,5′-	51908–16–8	360.878				310.0
147	2,2′,3,4′,5,6-	68194–13–8	360.878				310.0
148	2,2′,3,4′,5,6′-	74472–42–7	360.878				310.0
149	2,2′,3,4′,5′,6-	38380-04-0	360.878	oil		1	310.0
150	2,2′,3,4′,6,6′-	68194–08–1	360.878				310.0
151	2,2′,3,5,5′,6-	52663–63–5	360.878	101		0.180	310.0
152	2,2′,3,5,6,6′-	68194–09–2	360.878				310.0
153	2,2′,4,4′,5,5′-	35065-27-1	360.878	103.5		0.170	310.0
154	2,2′,4,4′,5,6′-	60145–22–4	360.878	oil		1	310.0
155	2,2′,4,4′,6,6′-	33979-03-2	360.878	112.5		0.139	310.0
156	2,3,3′,4,4′,5-	38380-08-4	360.878	127		0.100	310.0
157	2,3,3′,4,4′,5′-	69782–90–7	360.878				310.0
158	2,3,3′,4,4′,6	74472–42–7	360.878	107		0.157	310.0
159	2,3,3′,4,5,5′-	39635–35–3	360.878				310.0
160	2,3,3′,4,5,6-	41411–62–5	360.878	99		0.188	310.0
161	2,3,3′,4,5′,6-	74472–43–8	360.878				310.0
162	2,3,3′,4′,5,5′-	39635–34–2	360.878				310.0
163	2,3,3′,4′,5,6-	74472–44–9	360.878				310.0
164	2,3,3′,4′,5′,6-	74472–45–0	360.878				310.0
165	2,3,3′,5,5′,6-	74472–46–1	360.878				310.0
166	2,3,4,4′,5,6-	41411–63–6	360.878	163		0.0433	310.0
167	2,3′,4,4′,5,5′-	52663–72–6	360.878				310.0
168	2,3′,4,4′,5′,6-	59291–65–5	360.878	110–111		0.145	310.0
169	3,3′4,4′,5,5′-	32774-16-6	360.878	202		0.0183	310.0
170	2,2′,3,3′,4,4′,5-	35065-30-6	395.323	135		0.0833	330.9

continued

IUPAC no.	Congener	CAS no.	Molecular weight, MW g/mol	m.p. °C	b.p. °C	Fugacity ratio, F at 25°C*	Le Bas molar volume, V_M (cm³/mol)
171	2,2′,3,3′,4,4′,6-	52663-71-5	395.323	117.5		0.124	330.9
172	2,2′,3,3′,4,5,5′-	52663–74–8	395.323				330.9
173	2,2′,3,3′,4,5,6-	68194–16–1	395.323				330.9
174	2,2′,3,3′,4,5,6′-	38411–25–5	395.323	130.6		0.0920	330.9
175	2,2′,3,3′,4,5′,6-	40186–70–7	395.323				330.9
176	2,2′,3,3′,4,5,6′-	52663–65–7	395.323				330.9
177	2,2′,3,3′,4′,5,6-	52663–70–4	395.323				330.9
178	2,2′,3,3′,5,5′,6-	52663–67–9	395.323				330.9
179	2,2′,3,3′,5,6,6′-	52663–64–6	395.323				330.9
180	2,2′,3,4,4′,5,5′-	35065-29-3	395.323	110		0.147	330.9
181	2,2′,3,4,4′,5,6-	74472–47–2	395.323				330.9
182	2,2′,3,4,4′,5,6′-	60145–23–5	395.323	152		0.0567	330.9
183	2,2′,3,4,4′,5′,6-	52663–69–1	395.323	83		0.270	330.9
184	2,2′,3,4,4′,6,6′-	74472–48–3	395.323				330.9
185	2,2′,3,4,5,5′,6-	52712-05-7	395.323	149		0.0607	330.9
186	2,2′,3,4,5,6,6′-	74472–49–4	395.323				330.9
187	2,2′,3,4′,5,5′,6-	52663-68-0	395.323	149		0.0607	330.9
188	2,2′,3,4′,5,6,6′-	74487–85–7	395.323				330.9
189	2,3,3′,4,4′,5,5′-	39635–31–9	395.323	170		0.0378	330.9
190	2,3,3′,4,4′,5,6-	41411–64–7	395.323	117		0.125	330.9
191	2,3,3′,4,4′,5′,6-	74472–50–7	395.323				330.9
192	2,3,3′,4,5,5′,6-	74472–51–8	395.323				330.9
193	2,3,3′,4′,5,5′,6-	69782–91–8	395.323				330.9
194	2,2′,3,3′,4,4′,5,5′-	35694-08-7	429.768	159		0.0484	351.8
195	2,2′,3,3′,4,4′,5,6-	52663–78–2	429.768				351.8
196	2,2′,3,3′,4,4′,5,6′-	42740–50–1	429.768				351.8
197	2,2′,3,3′,4,4′,6,6′-	33091–17–7	429.768	132		0.0892	351.8
198	2,2′,3,3′,4,5,5′,6-	68194–17–2	429.768				351.8
199	2,2′,3,3′,4,5,5′,6′-	52663–75–9	429.768				1.759
200	2,2′,3,3′,4,5,6,6'-	52663–73–7	429.768				351.8
201	2,2′,3,3′,4,5′,6,6′-	40186–71–8	429.768				351.8
202	2,2′,3,3′,5,5′,6,6′-	2136-99-4	429.768	161		0.0463	351.8
203	2,2′,3,4,4′,5,5′,6-	52663–76–0	429.768				351.8
204	2,2′,3,4,4′,5,6,6′-	74472–52–9	429.768				351.8
205	2,3,3′,4,4′,5,5′,6-	74472–53–0	429.768				351.8
206	2,2′,3,3′,4,4′,5,5′,6-	40186-72-9	464.213	206		0.0168	372.7
207	2,2′,3,3′,4,4′,5,6,6′-	52663-79-3	464.213				372.7
208	2,2′,3,3′,4,5,5′,6,6′-	52663-77-1	464.213	180.5		0.0298	372.7
209	2,2′,3,3′,4,4′,5,5′,6,6′-	2051-24-3	498.658	309		0.00164	393.6

Table 6: Summary of Physical Properties of PCB Isomer Groups and Aroclor Mixtures

PCB isomer group	CAS no.	Molecular weight, MW g/mol	Cl no.	m.p. °C	Fugacity ratio, F range at 25°C	Le Bas molar volume, V_M (cm³/mol)
Biphenyl	92-52-4	154.2	0	71	0.352	184.6
Monochloro-	27323-18-8	188.7	1	25.1–78	0.299–1.0	205.5
Dichloro-	25512-42-9	223.1	2	24.4–149	0.0594–1.0	226.4
Trichloro-	25323-68-6	257.5	3	28.1–102	0.173–0.932	247.3
Tetrachloro-	26914-33-0	292.0	4	47–164	0.042–0.606	268.2
Pentachloro-	25429-29-2	326.4	5	76.5–123	0.107–0.310	289.1
Hexachloro-	26601-64-9	360.9	6	70–201	0.0182–0.359	310
Heptachloro-	28655-71-2	395.3	7	109–162	0.0596–0.148	330.9
Octachloro-	31472-83-0	429.8	8	132–161	0.0452–0.0874474	351.8
Nonachloro-	53742-07-7	464.2	9	205–206	0.0163–0.0276	372.7
Decachloro-	2051-24-3	498.7	10	305	0.00167	393.6

Aroclor mixture	CAS no.	Molecular weight, MW g/mol	% Cl	No. of Cl/molecule	Fugacity ratio, F at 25°C	Density g/cm³ at 25°C	Distillation range °C
Aroclor 1016	12674-11-2	257	41	3	1.0	1.33	323–356
Aroclor 1221	111-042-82	192	20.5–21.5	1.15	1.0	1.15	275–320
Aroclor 1232	111-411-65	221	31.4–32.5	2.04	1.0	1.24	290–325
Aroclor 1242	534-692-19	261	42	3.1	1.0	1.35	325–366
Aroclor 1248	126-722-96	288	48	3.9	1.0	1.41	340–375
Aroclor 1254	110-976-91	327	54	4.96	1.0	1.5	365–390
Aroclor 1260	110-968-25	372	60	6.3	1.0	1.58	385–420

CHAPTER 3

DESIGN OF THE STUDY

Methodology

Extraction and Clean-up

All Transformer-oil were collected randomly from electrical transmission. 0.5 gram of transformer oils were placed in 9 different test-tubes covered with aluminum foil and placed in a test-tube stand. Each containing 0.5 grams of collected transformer-oil sample in a test-tube and 3mL of Hexane, 5ppm of internal Standard (Decachlorobiphenyls) and 1mL of concentrated Sulfuric acid (H2SO4) was added to each sample. Each sample test-tube was vortex for 3 minutes for mixture until it became homogenized and centrifuge at 3140 - 3300rpm for 5 minutes one time. The Sulfuric acid (H2SO4) layer at bottom of each sample was removed. The extraction with hexane on the samples were performed 3 times until samples brownish colors were removed. Each sample was washed with 5% aquatic solution of Potassium permanganate for clean-up (EPA Method 3665). The samples were concentrated, and they were prepared for analysis.

Instrumental Analysis

GCMS

The GC - Column used Agilent 19091S-433 HP-SMS 5% Phenyl Methyl Silox, with temperature range of 0 – 325-degree centigrade and 30 m x 250 um x 0.25um. Gas – Helium;

Helium; Run time - 30.286 min, post run time -10 min; Mode – spitless, Heater on 250 degree centigrade, Pressure on 250 degree centigrade, Pressure on 19.346 psi, Total flow on 104 mL/min; Oven:- equilibration time – 0.25min, Max temp – 325 degree centigrade, Max temperature – disable, Slow fan – disabled, Post run – 325 degree centigrade, Program #1 – 7 /min, #1 Value – 325, # hold time – 0min; Syringe size - 10 µl, Injection Vol – 1 µl; Solvent wash mode A, B; Solvent A washes (pre-in) 3, Solvent A washes (post-in) 3, Solvent A volume 8uL, Solvent B washes (pre-in) – 0, Solvent washes (post-in) – 0, Solvent B volume – 8 µl, Sample washes – 3, Sample washes volume - 1 µl, Sample pumps – 3, Sample wash draw speed 300 µl /min, Sample wash dispense speed 300 µl /min; Dwell time (pre- in) – 0min, Dwell time (post- in) - 0min; Solvent wash draw speed – 300 µl /min, Solvent wash dispense speed 300 µl /min, Injection – standard, Li Air gap – 0.2 µl, Injection wash dispense speed - 600 µl /min, Viscosity delay – 0 sec, , Septrum purge flow mode – switched, Septrum purge flow – on 3L/min Run time 650 mins.

Figure 2: Image of Agilent Technologies GC System (7890B)

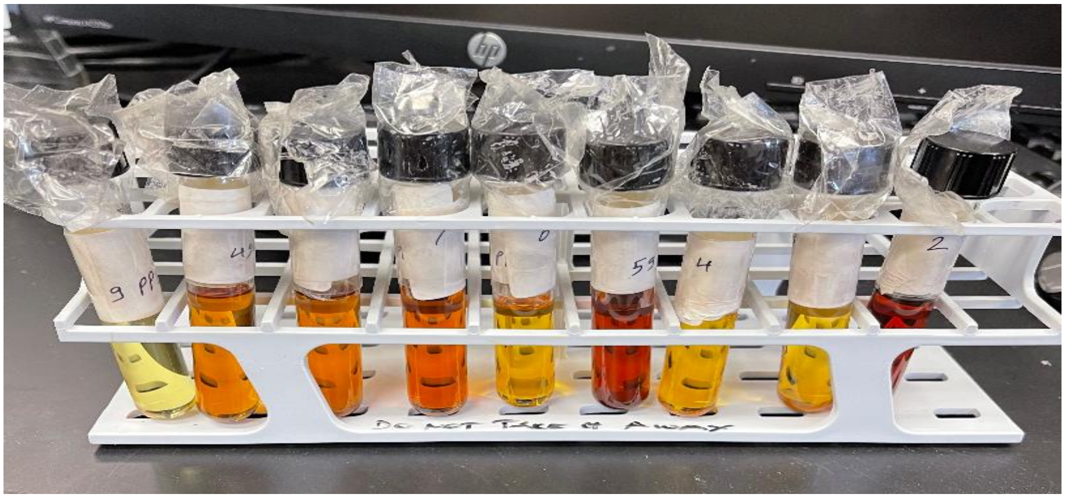

Figure 3: Nine Random Samples of Transformer Oil

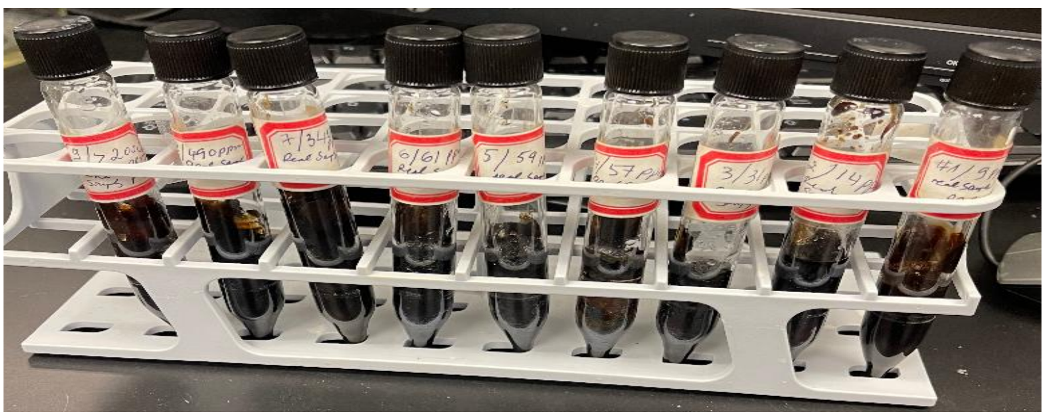

Figure 4: Nine Samples of Transformer Oil in Extraction Process

Figure 5: Image of Cleaned Nine Samples of Transformer Oil in GC Vials

CHAPTER 4

RESULTS AND DISCUSSION

Calibration Curve

The calibration curve was generated using the Microsoft Excel for the calculated total ecd area vs concentration (ppm) of the blank oil (0ppm) and five standards (of 20 ppm, 40 ppm, 60 ppm, 80 ppm, and 100 ppm) (Figure). The Calibration equation: Y=20.485X-21.207 was used to calculate the concentration of PCB in each given sample.

where Y is the total peaks area and x is the sample concentration.

X=sample total peaks area +21.207/20.48 ppm

Table 7: Concentration of Internal Standard vs Total Area for Calibration Curve

Concentration ppm	Total Area
Blank Oil	0.69
20 ppm	19.48
40 ppm	37.83
60 ppm	59.47
80 ppm	83.60
100 ppm	101.49

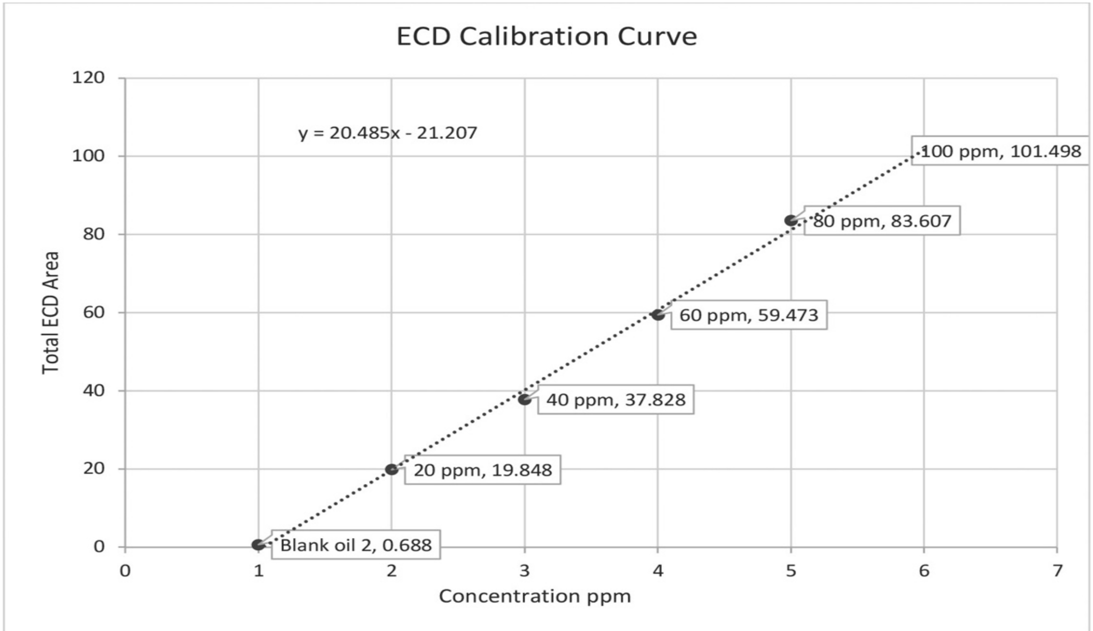

Figure 6: ECD Calibration Curve

STANDARD CHROMATOGRAM (SIM/ECD)

STANDARD 1

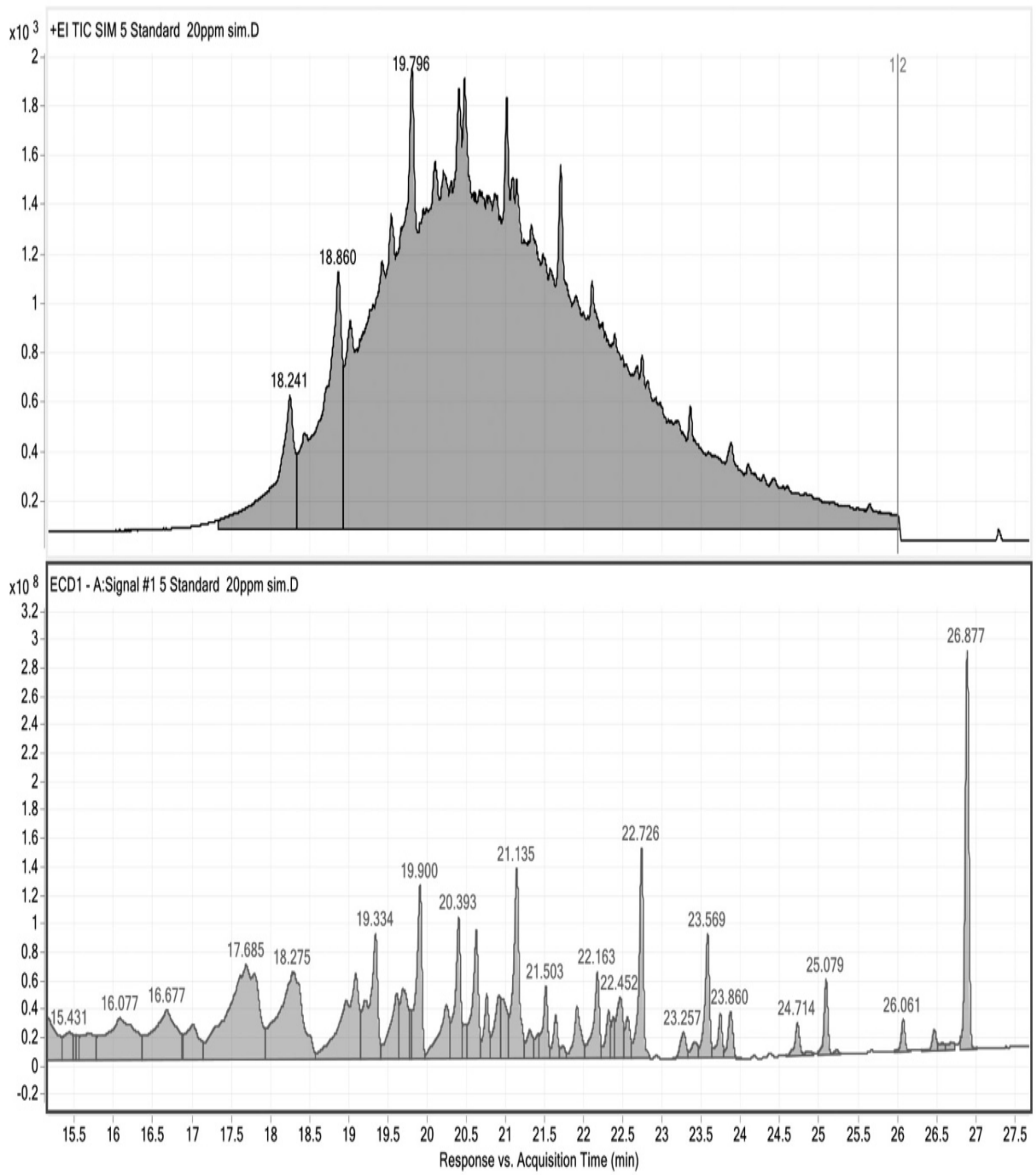

Figure 7: Standard 1, 20 ppm SIM/ECD Chromatogram

STANDARD 2

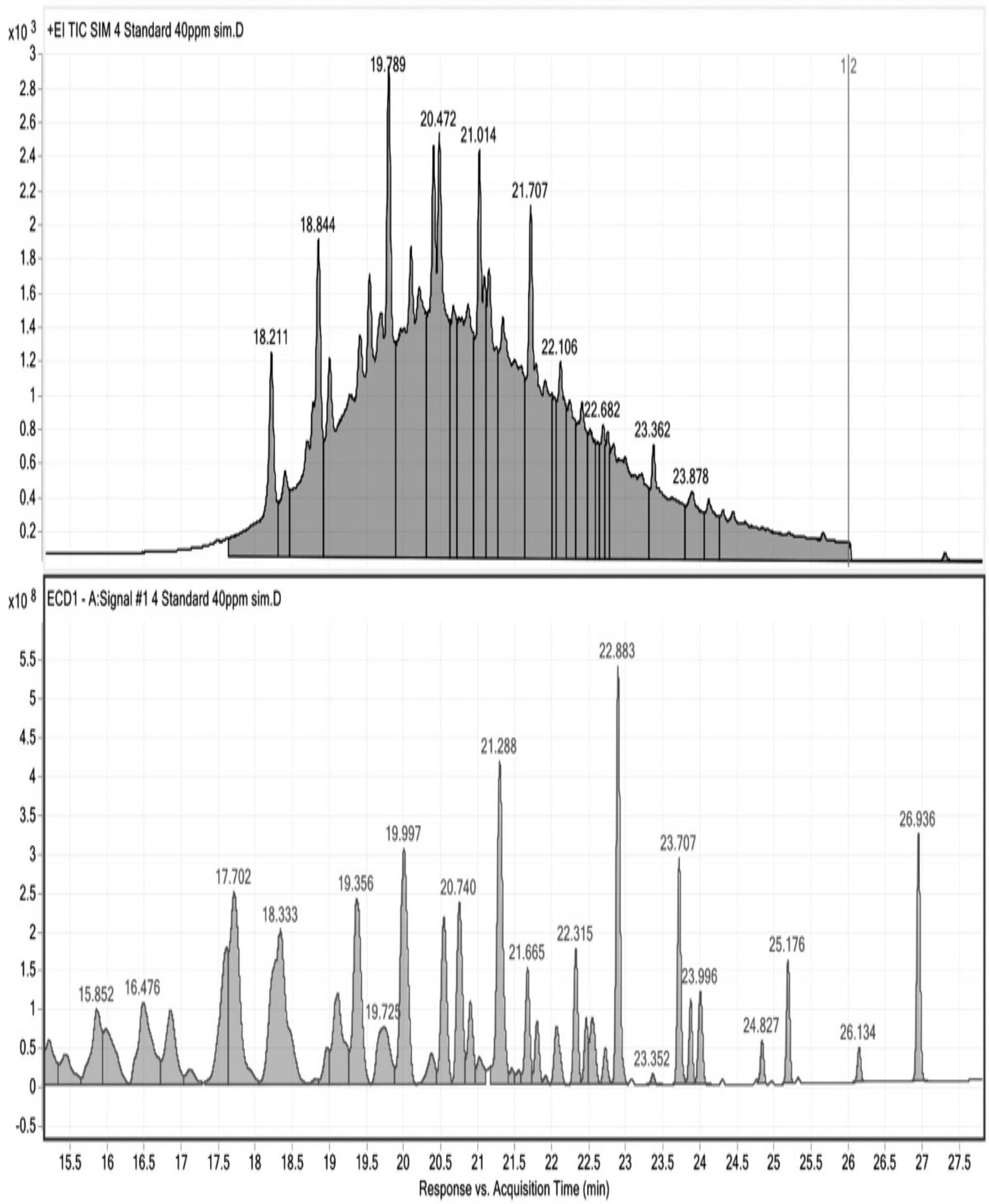

Figure 8: Standard 2, 40 ppm SIM/ECD Chromatogram

STANDARD 3

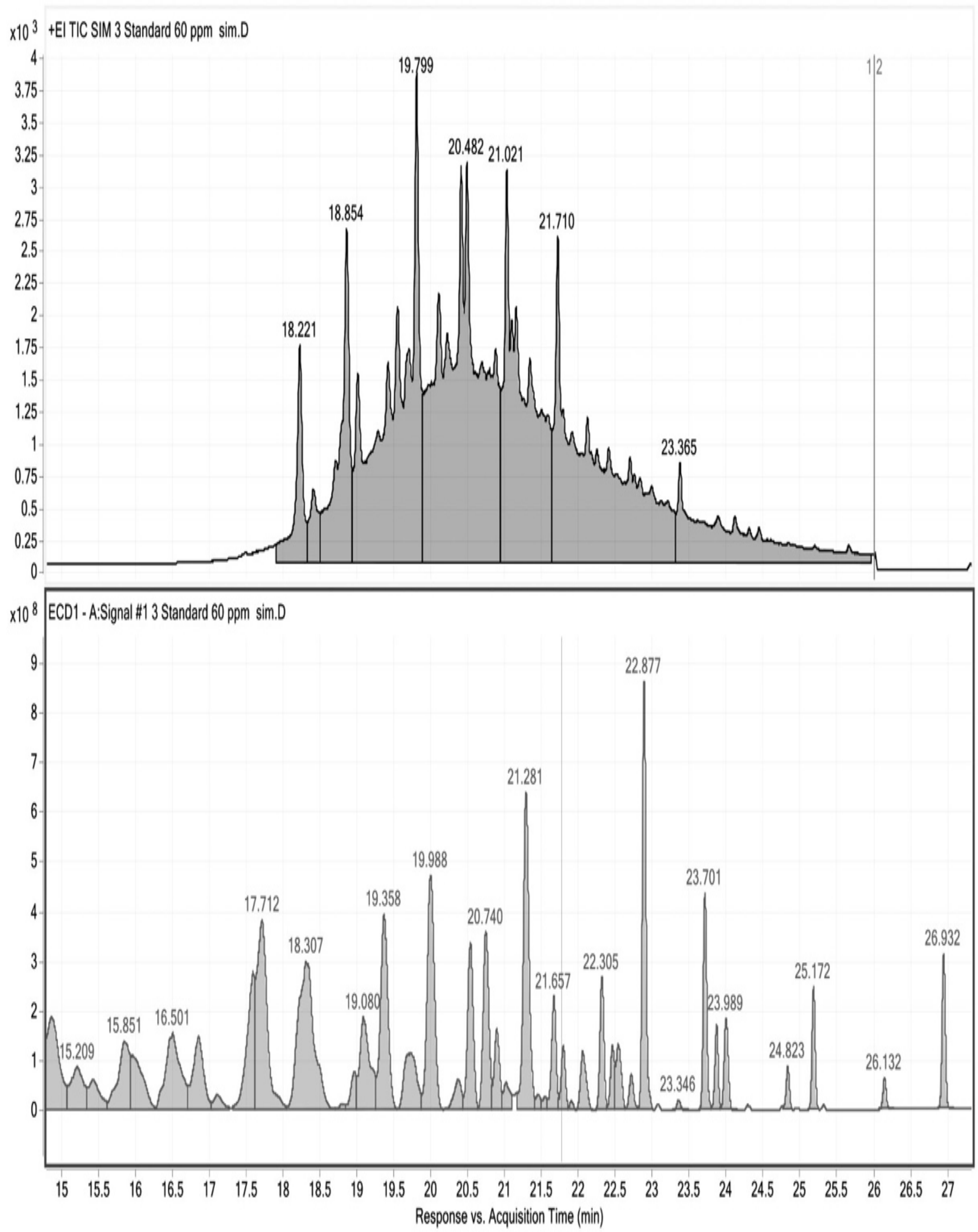

Figure 9: **Standard 3, 60 ppm SIM/ECD Chromatogram**

STANDARD 4

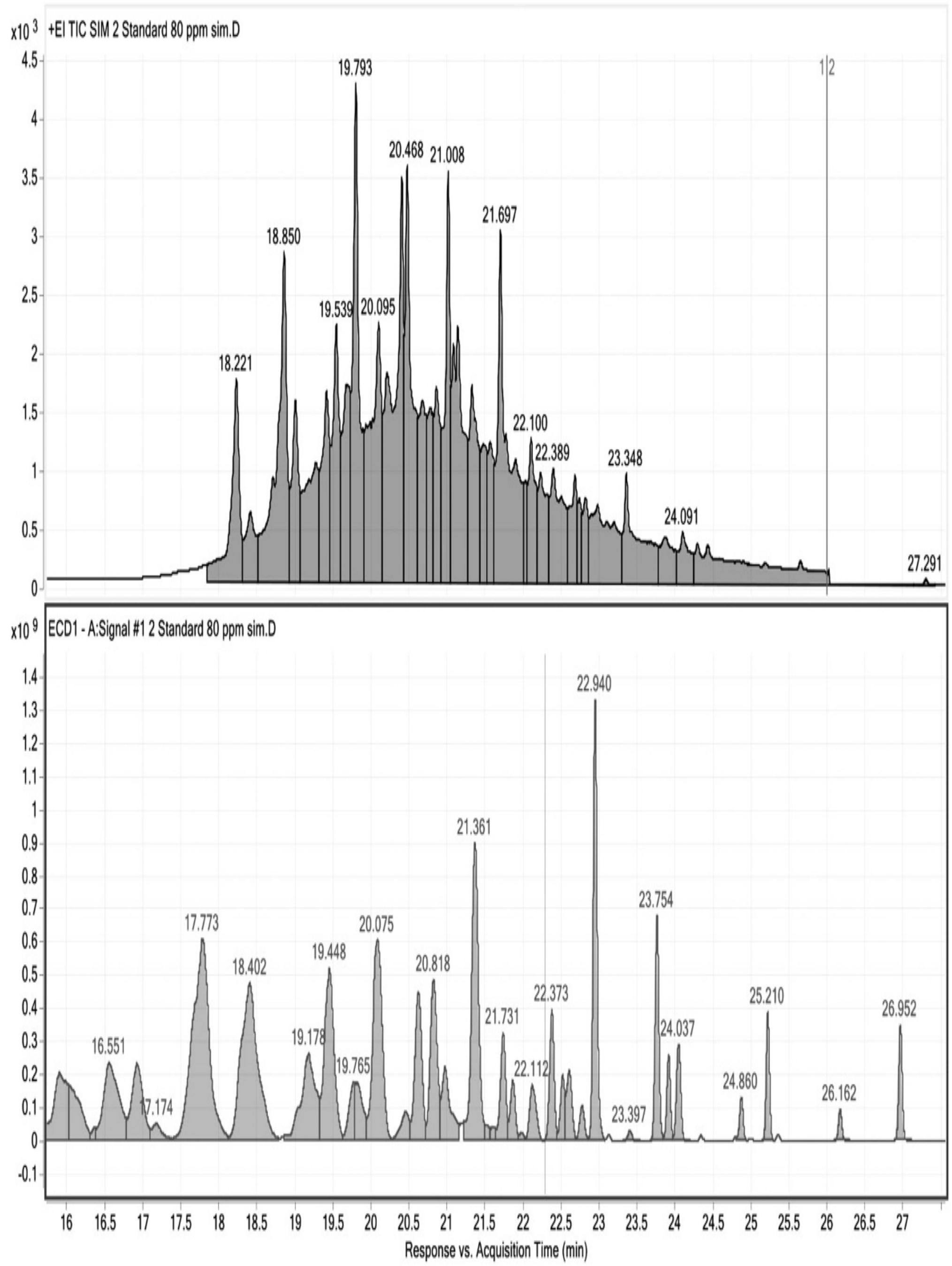

Figure 10: Standard 4, 80 ppm SIM/ECD Chromatogram

STANDARD 5

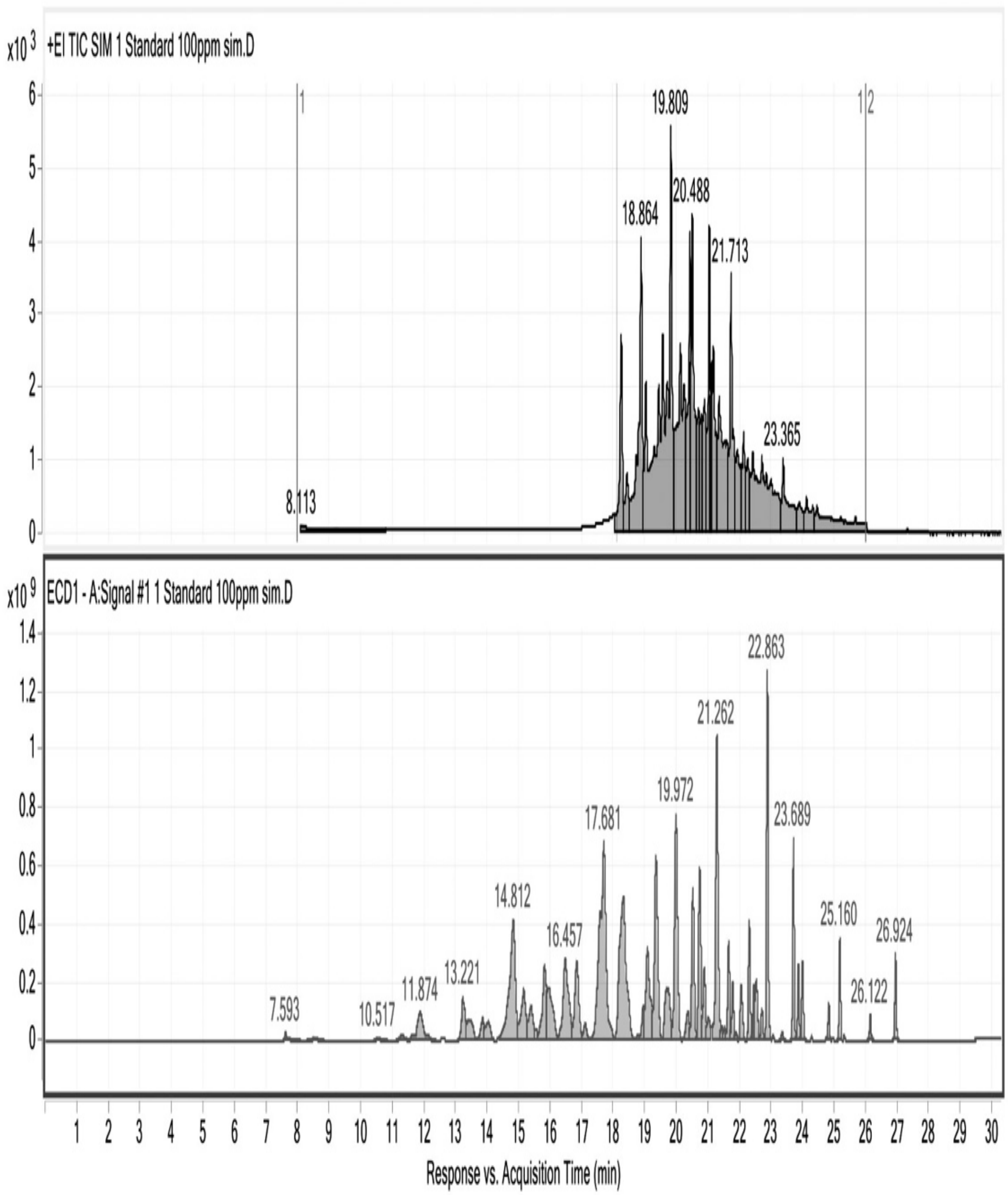

Figure 11: Standard 5, 100 ppm SIM/ECD Chromatogram

The Concentration of PCBs in Samples

Sample 1: 2.44 ppm

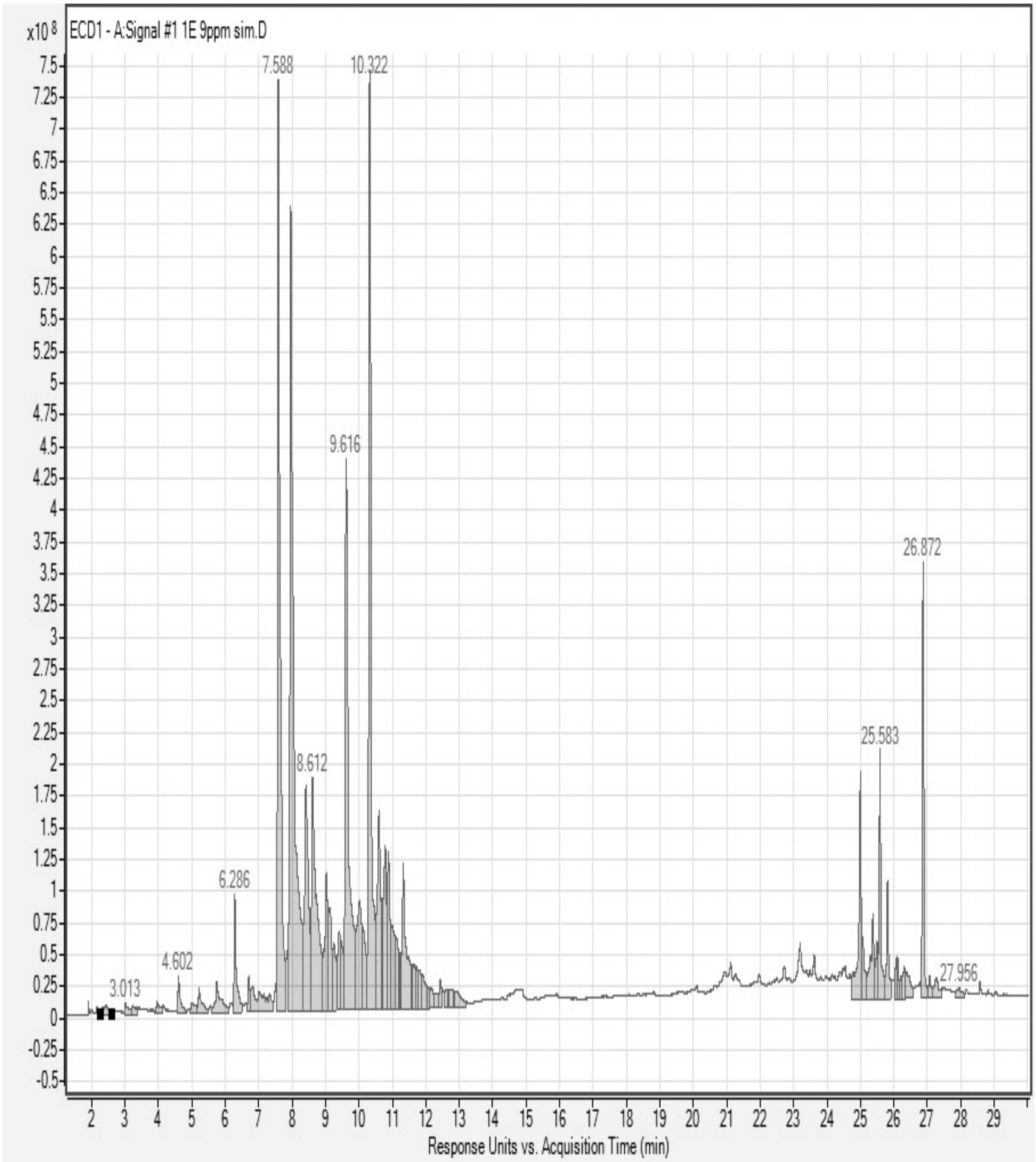

Figure 12: Sample 1, 2.44 ppm of transformer oil ECD result

Sample 2: 2.19 ppm

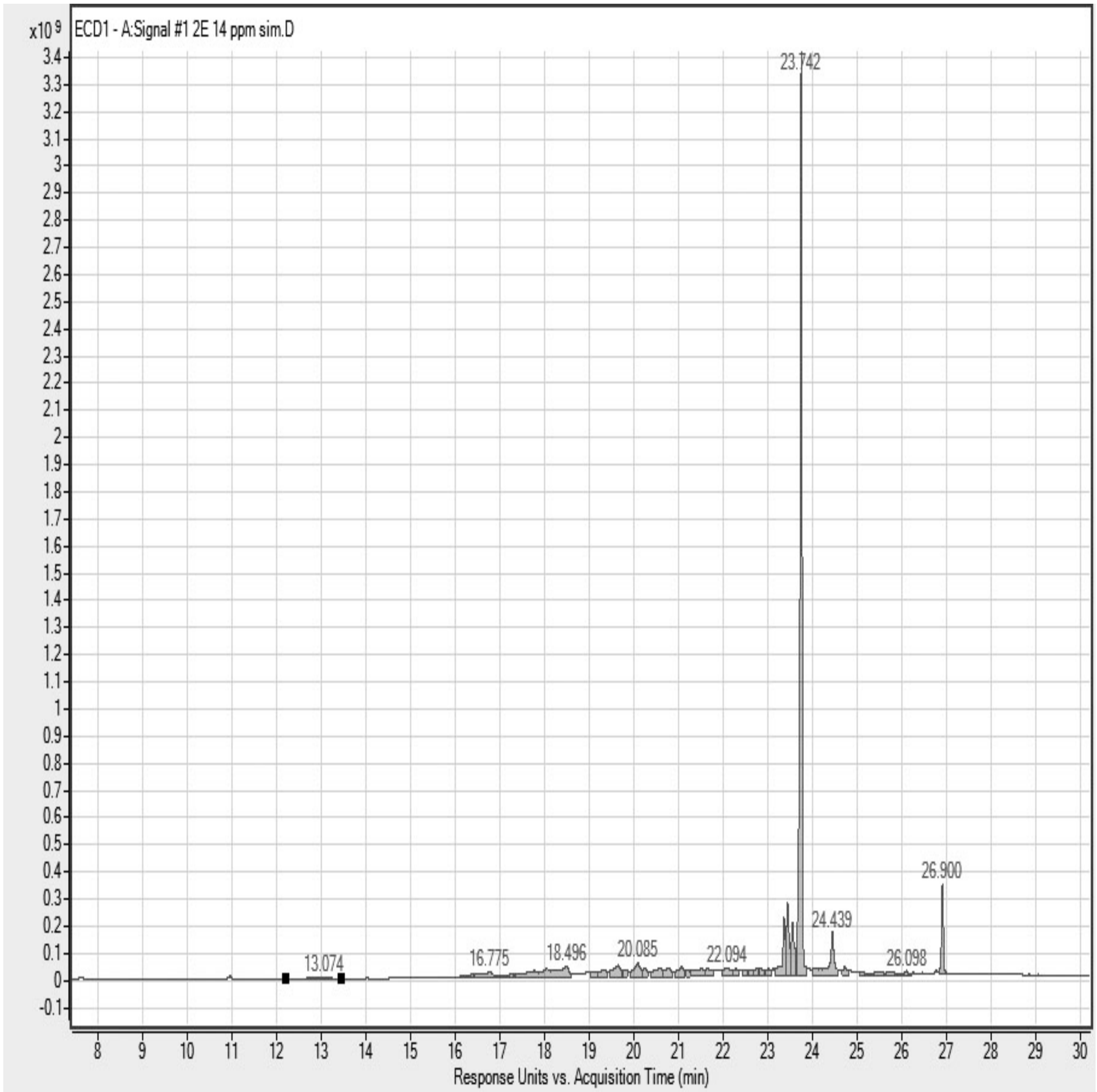

Figure 13: Sample 2, 2.19 ppm of Transformer Oil ECD Result

Sample 3: 1.63 ppm

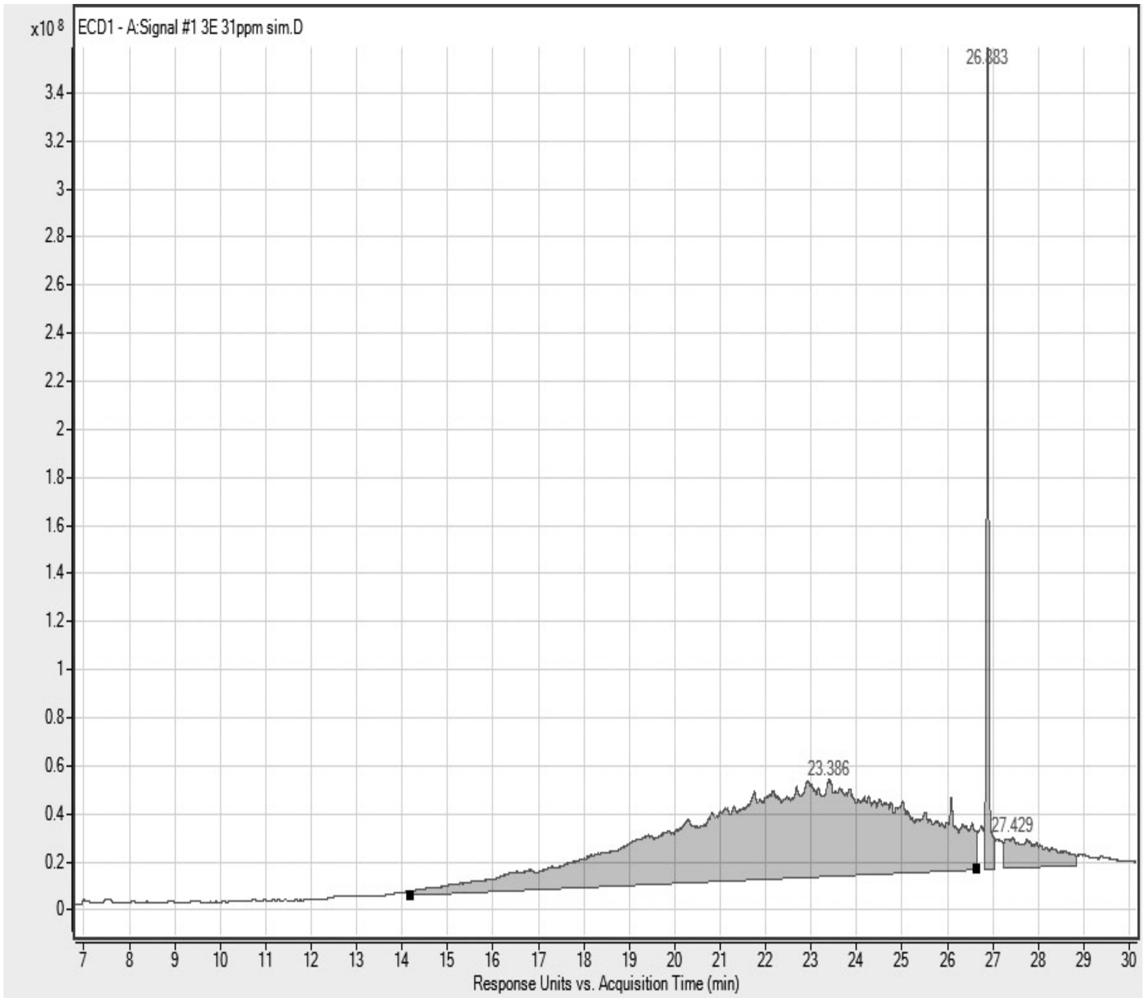

Figure 14: Sample 3, 1.63 ppm of transformer oil ECD result

Sample 4: 2.56 ppm

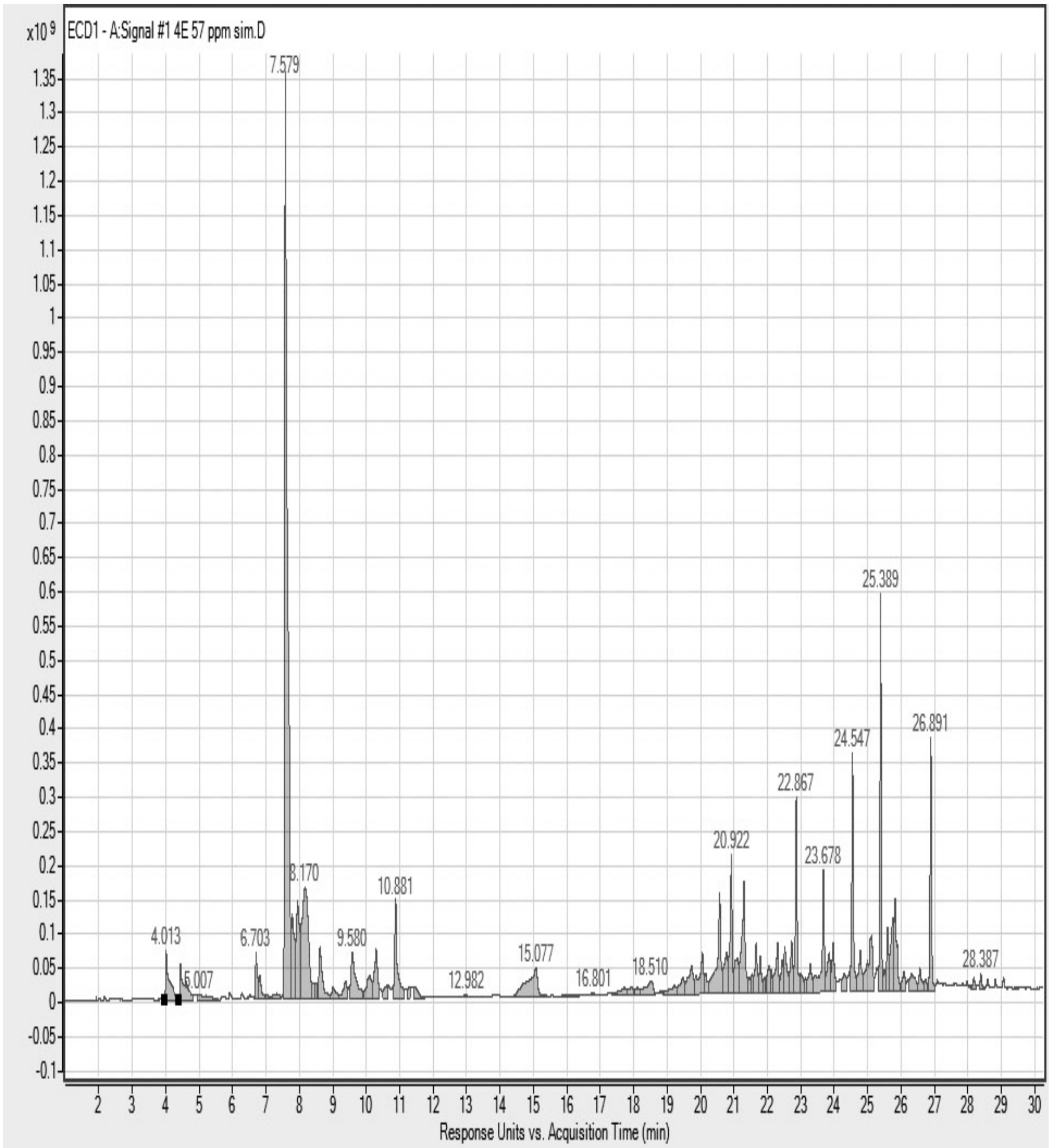

Figure 15: Sample 4, 2.56 ppm of Transformer oil ECD Result

Sample 5: 5.24 ppm

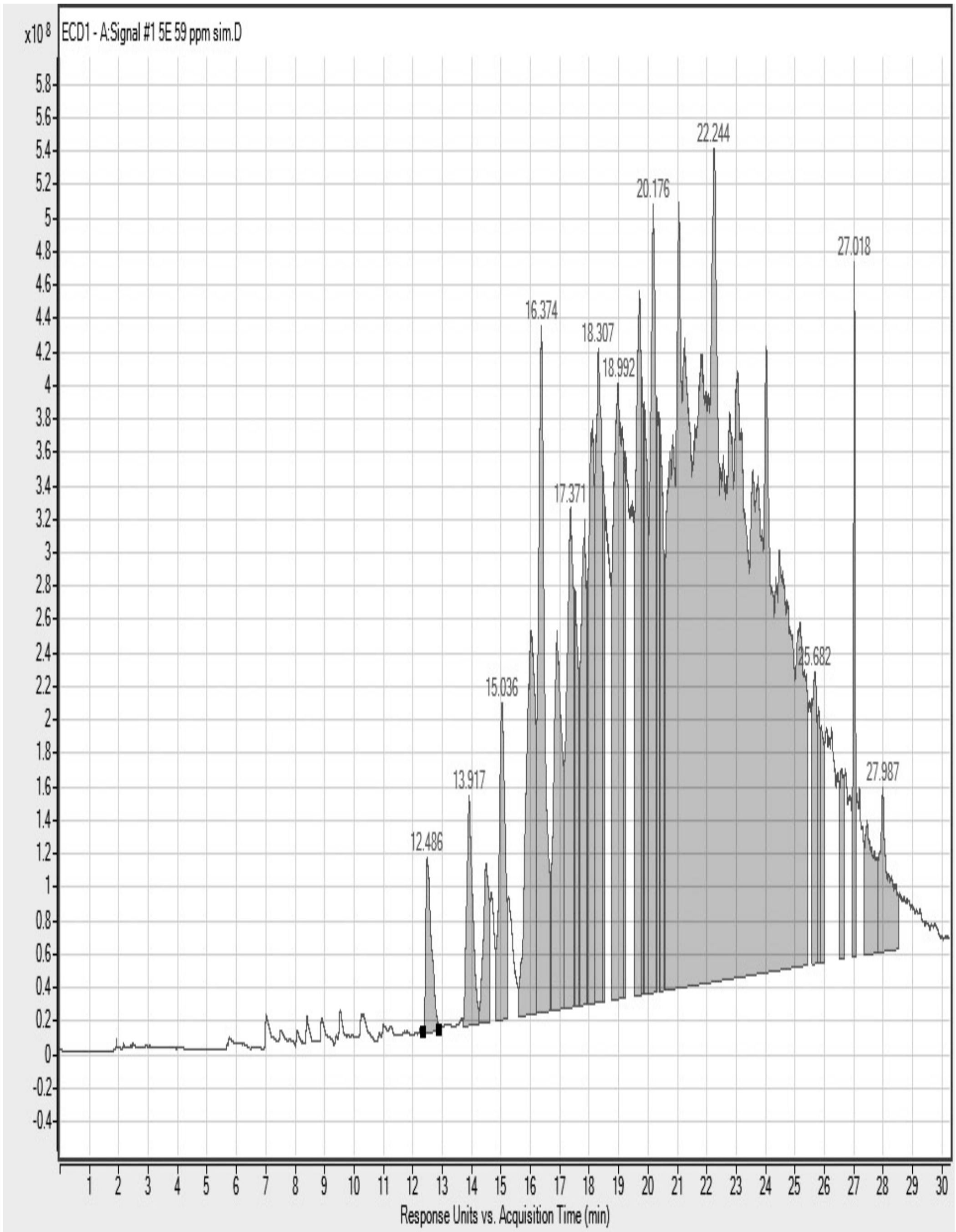

Figure 16: Sample 5, 5.24 ppm of Transformer Oil ECD Result

Sample 6: 2.54 ppm

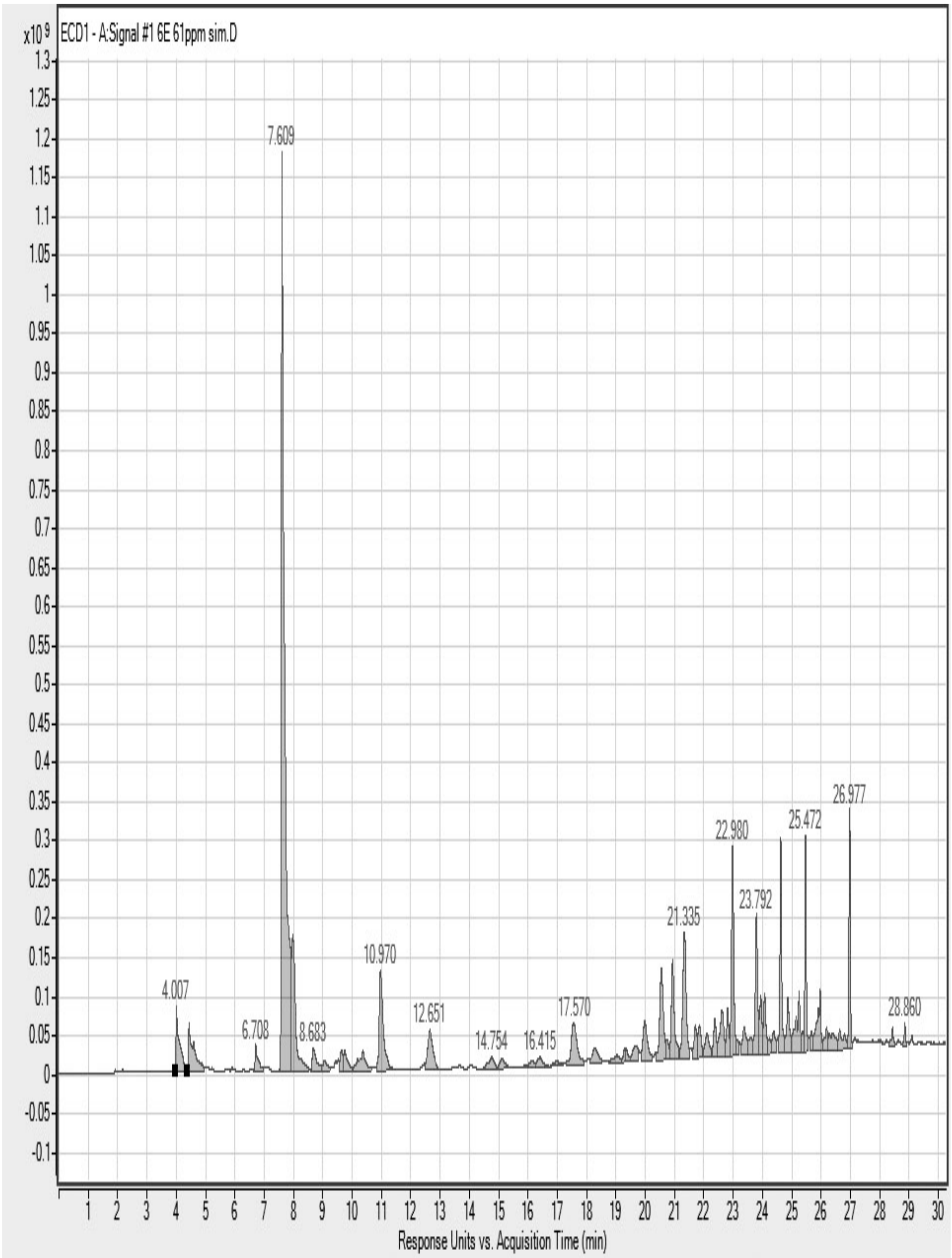

Figure 17: Sample 6, 2.54 ppm of Transformer Oil ECD Result

Sample 7: 3.62 ppm

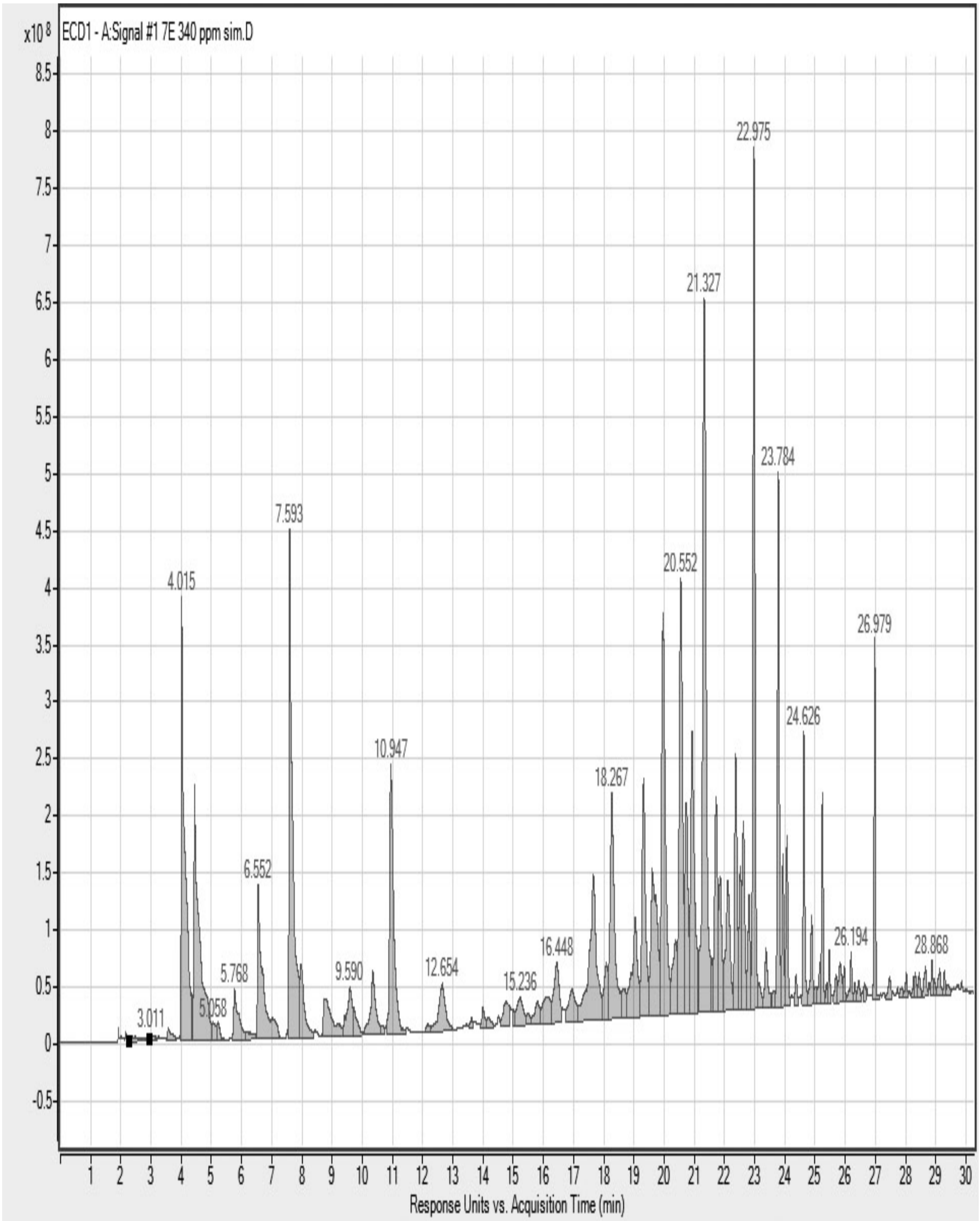

Figure 18: Sample 7, 3.62 ppm of Transformer Oil ECD Result

Sample 8: 1.72 ppm

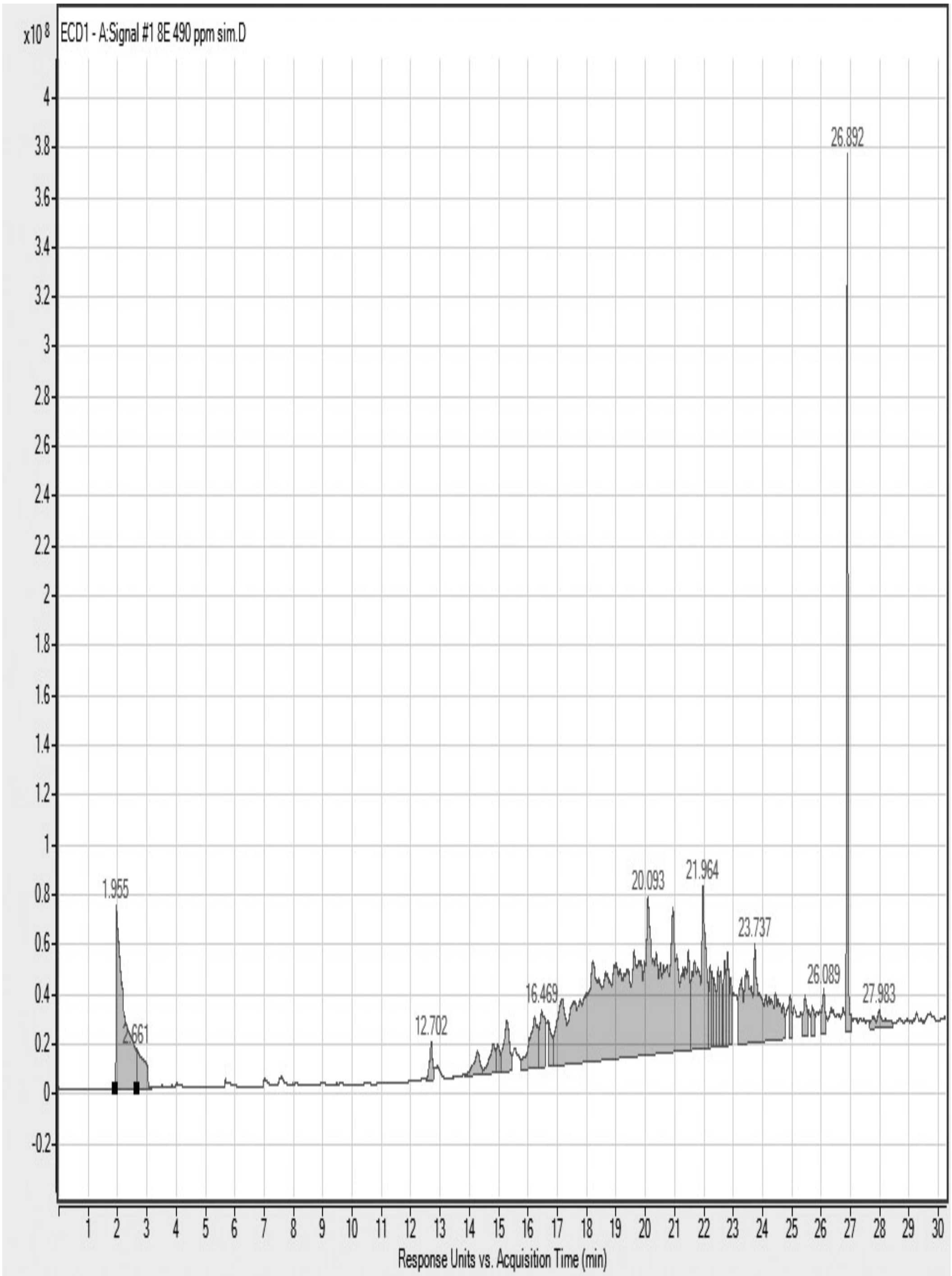

Figure 19: Sample 8, 1.72 ppm of Transformer Oil ECD Result

Sample 9: 15.57 ppm

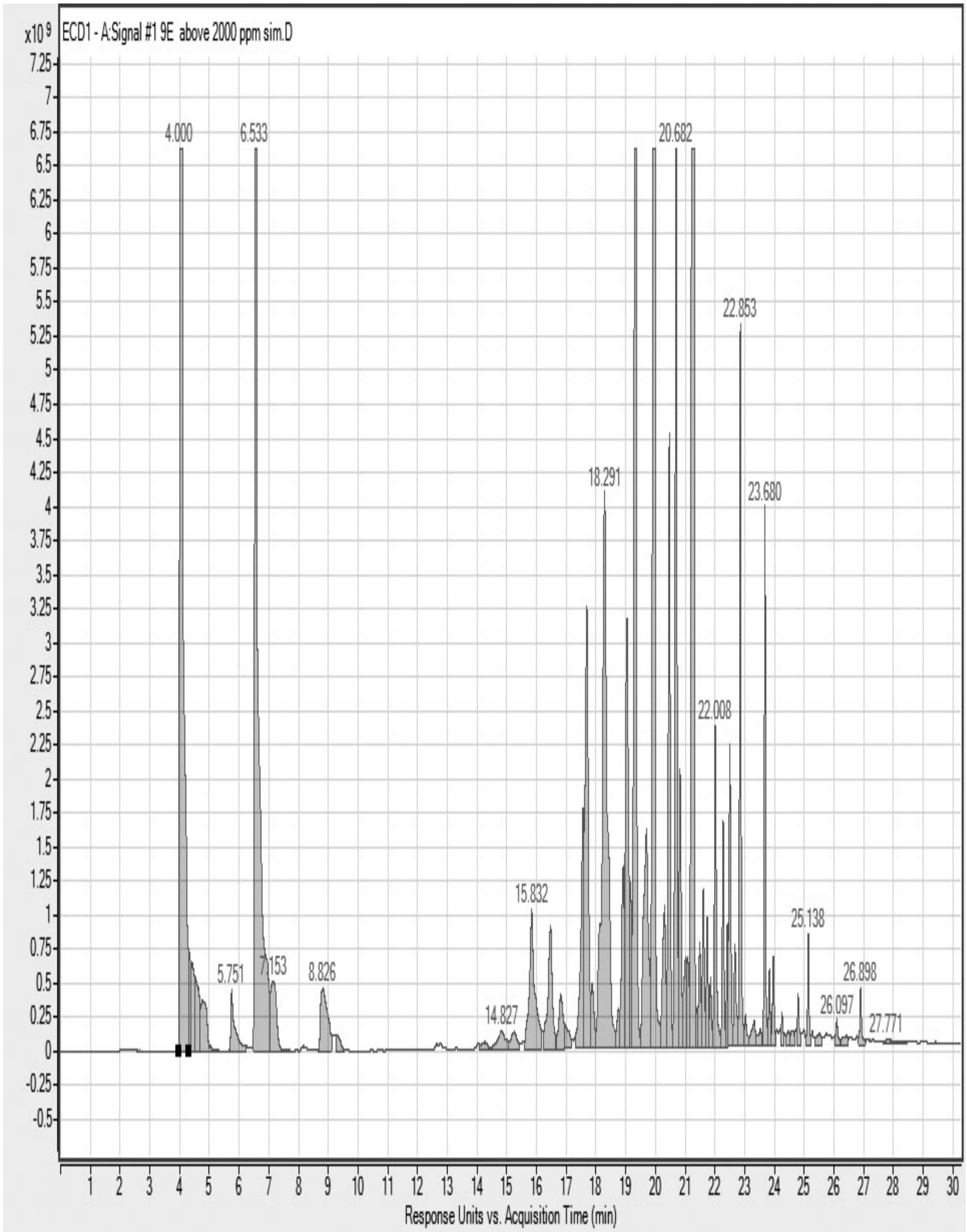

Figure 20: Sample 9, 15.57 ppm of Transformer Oil ECD Result

PCB Commercial Samples

Difference between ECD and MSD chromatogram: ECD chromatogram doesn't have the information about the structure, however MSD has the structural information. ECD is very sensitive and has much better detection and the size of the peak in ECD is much bigger than MSD and it corresponds to number of chlorine molecules in the sample. Whereas MSD chromatogram is independent of the chlorine molecules and gives structural information.

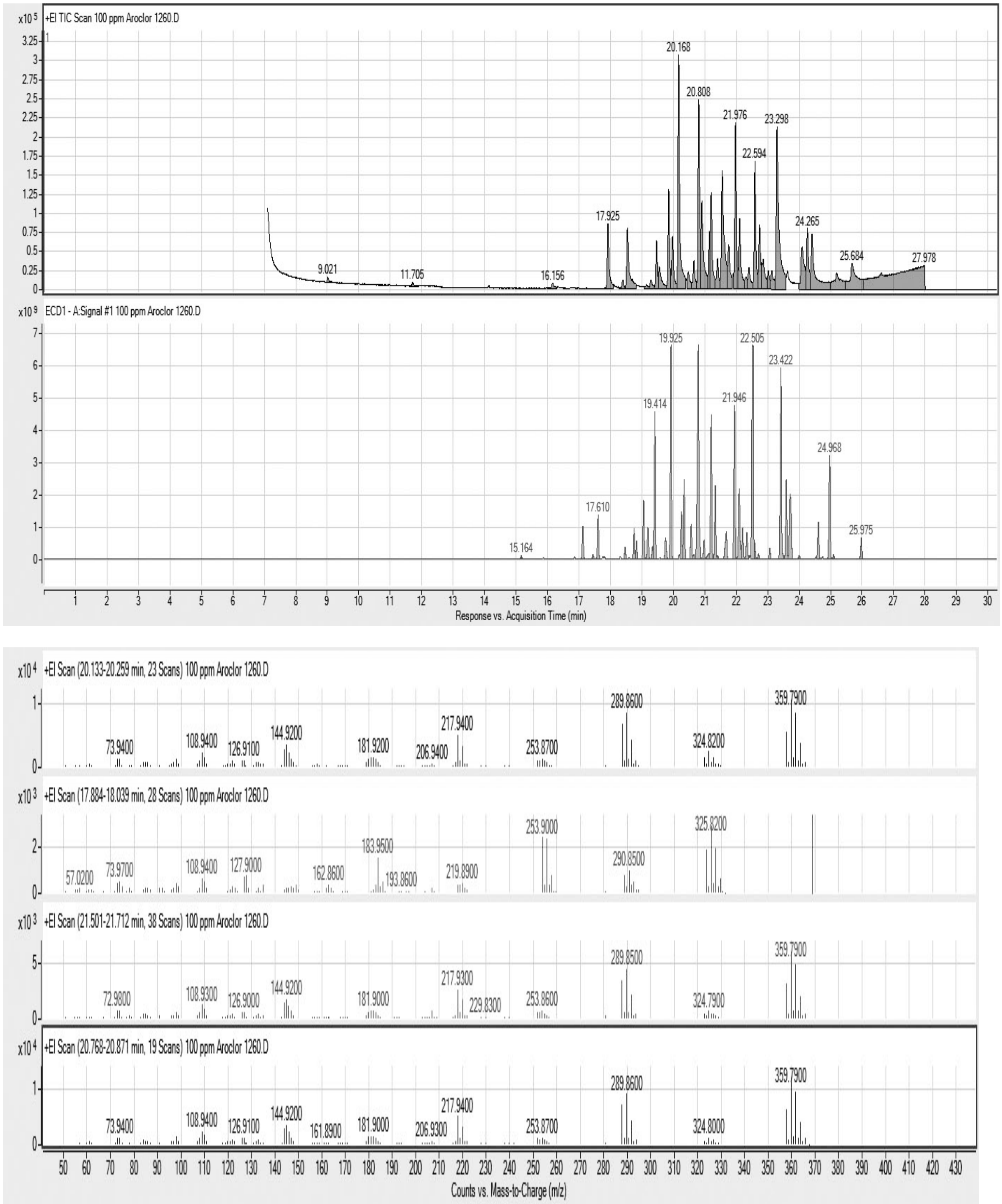

Figure 21: Aroclor 100 ppm 1260 MSD/ECD

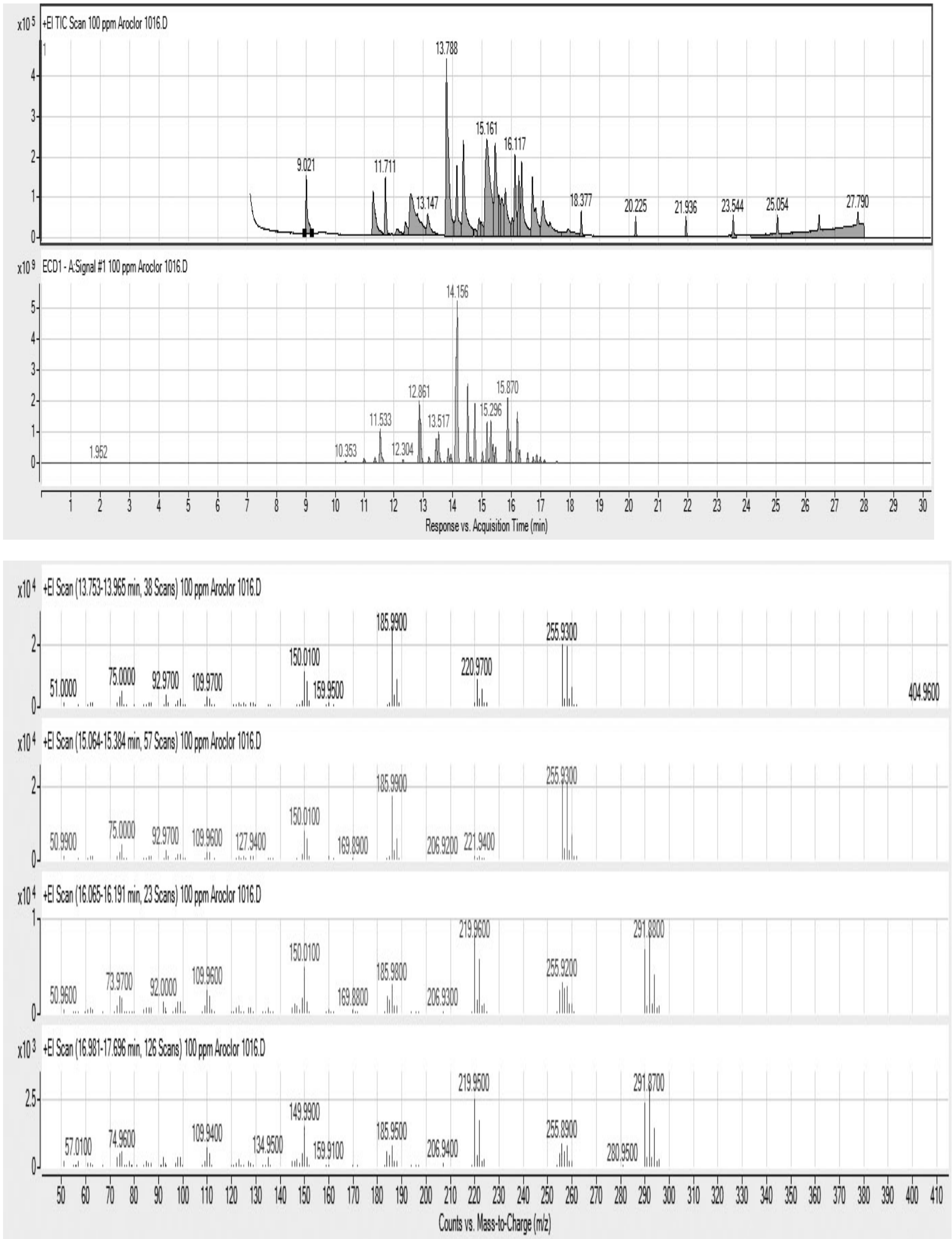

Figure 22: Aroclor 100 ppm 1016 MSD/ECD

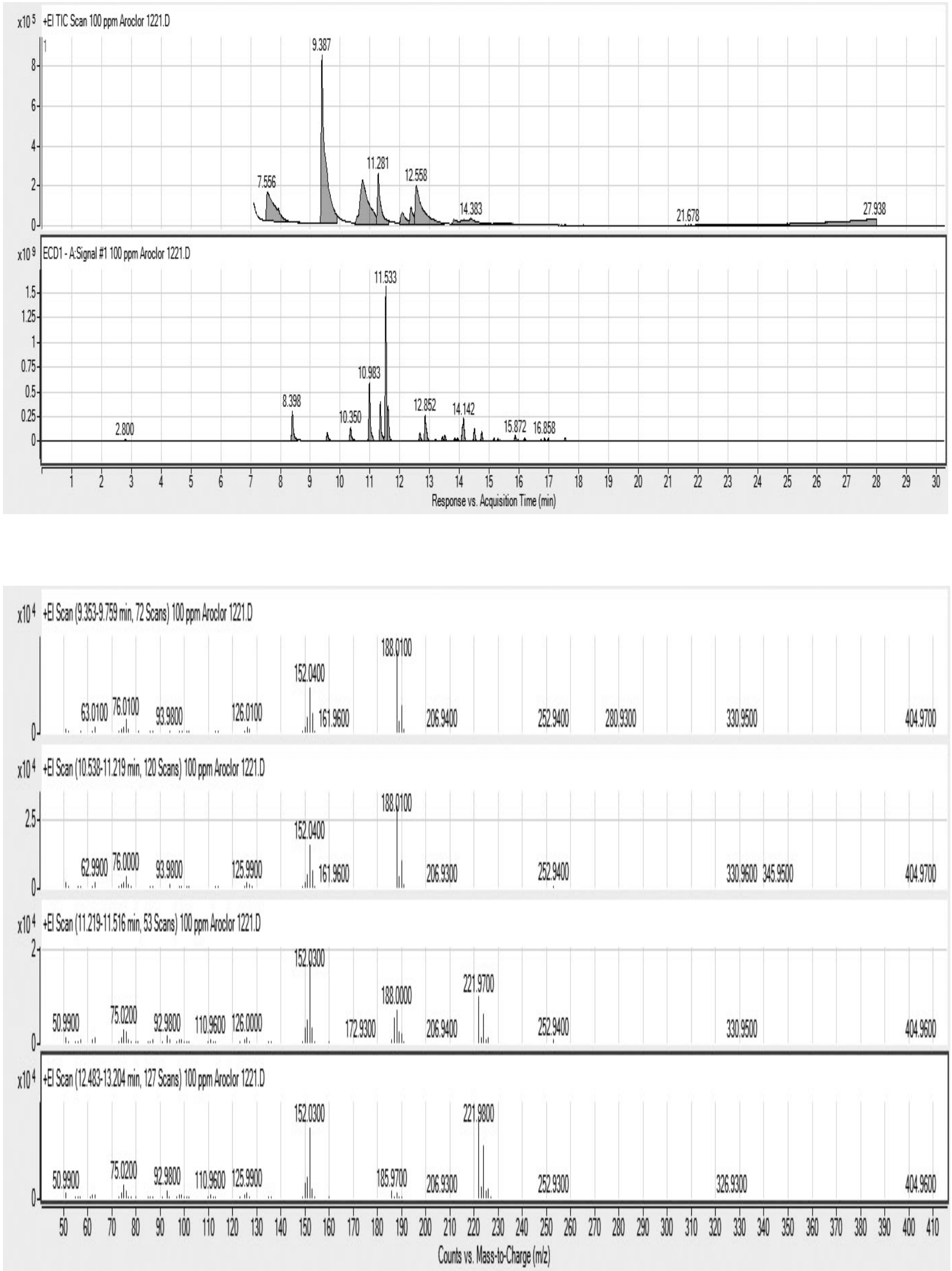

Figure 23: Aroclor 100 ppm 1221 MSD/ECD

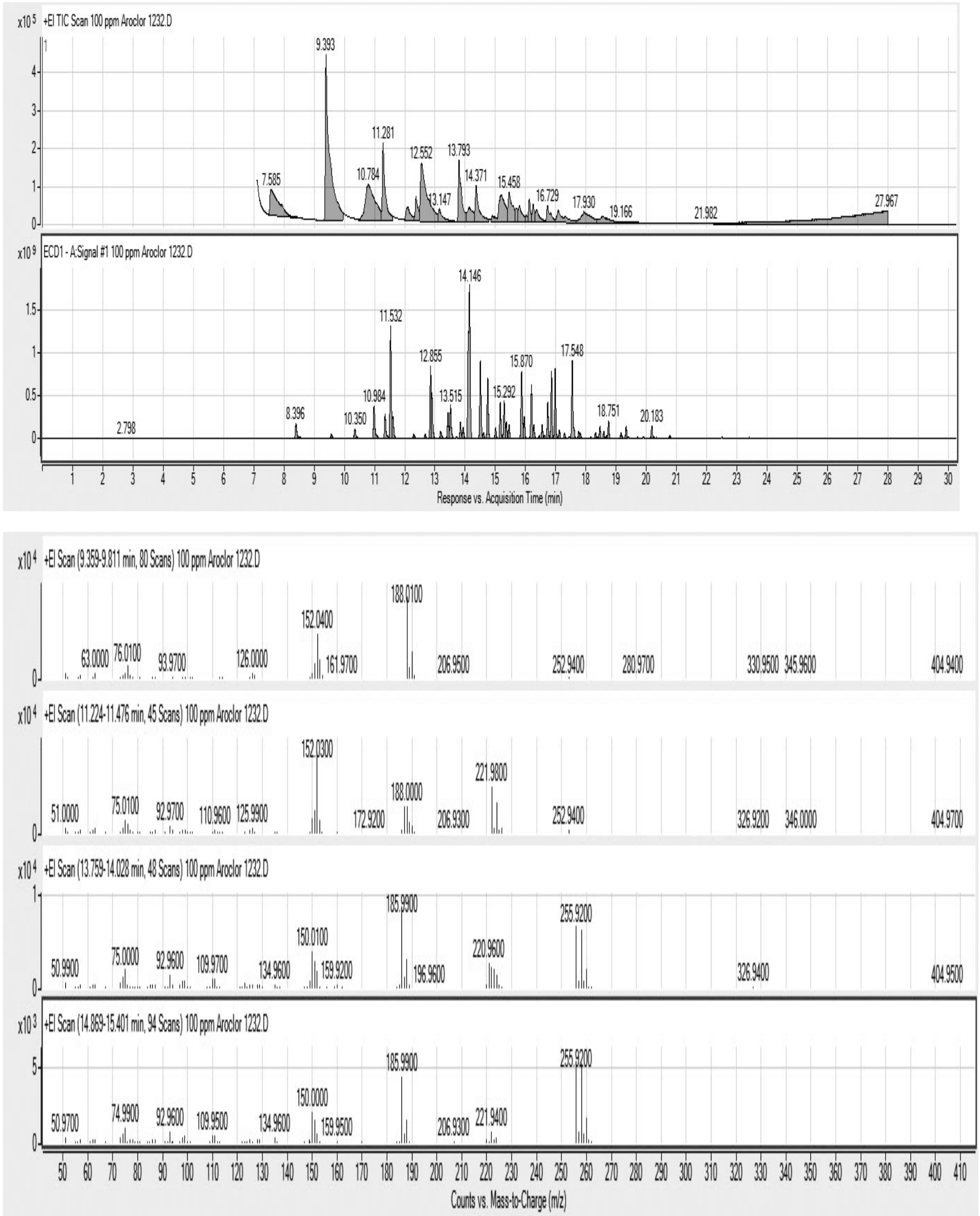

Figure 24: Aroclor 100 ppm 1232 MSD/ECD

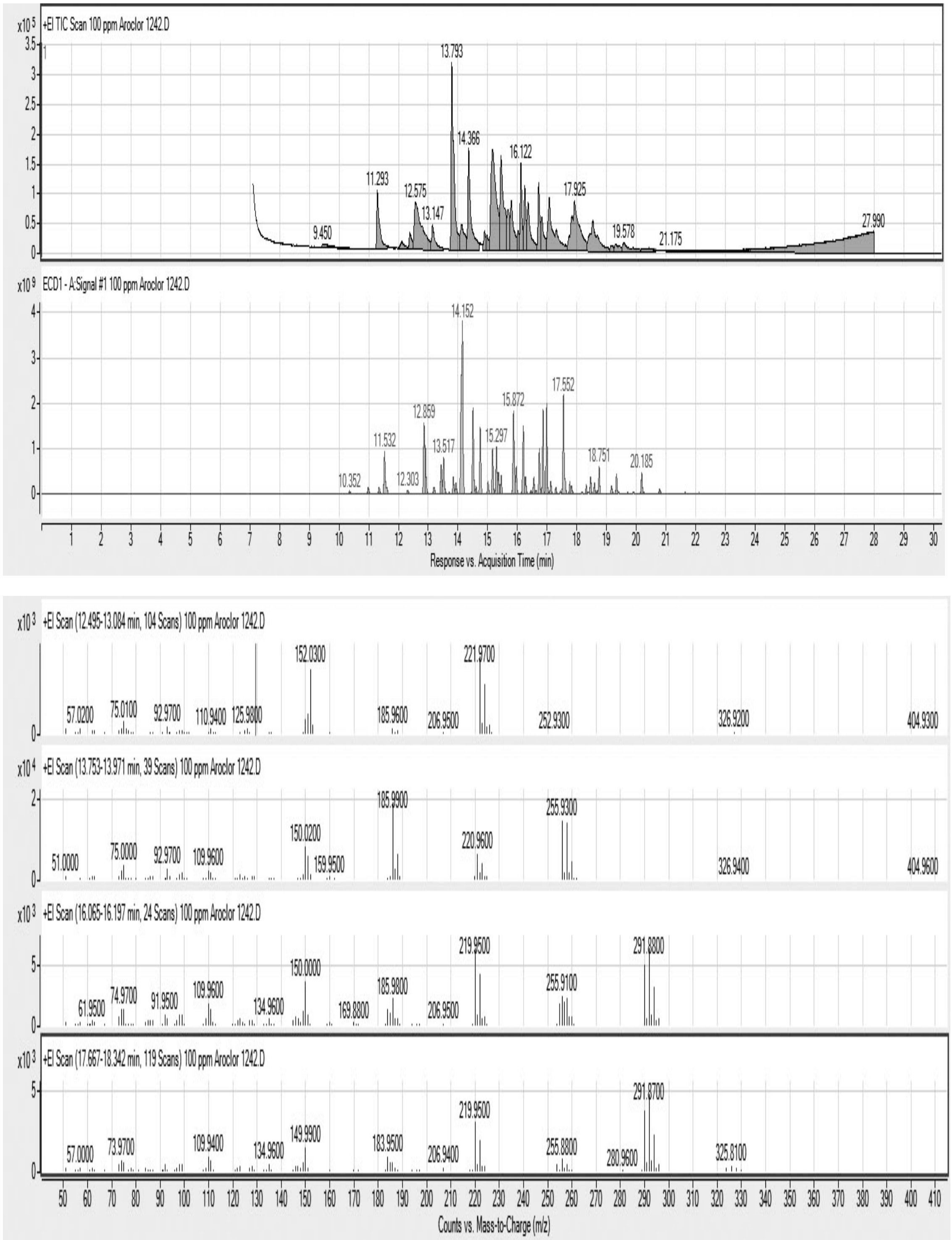

Figure 25: Aroclor 100 ppm 1242 MSD/ECD

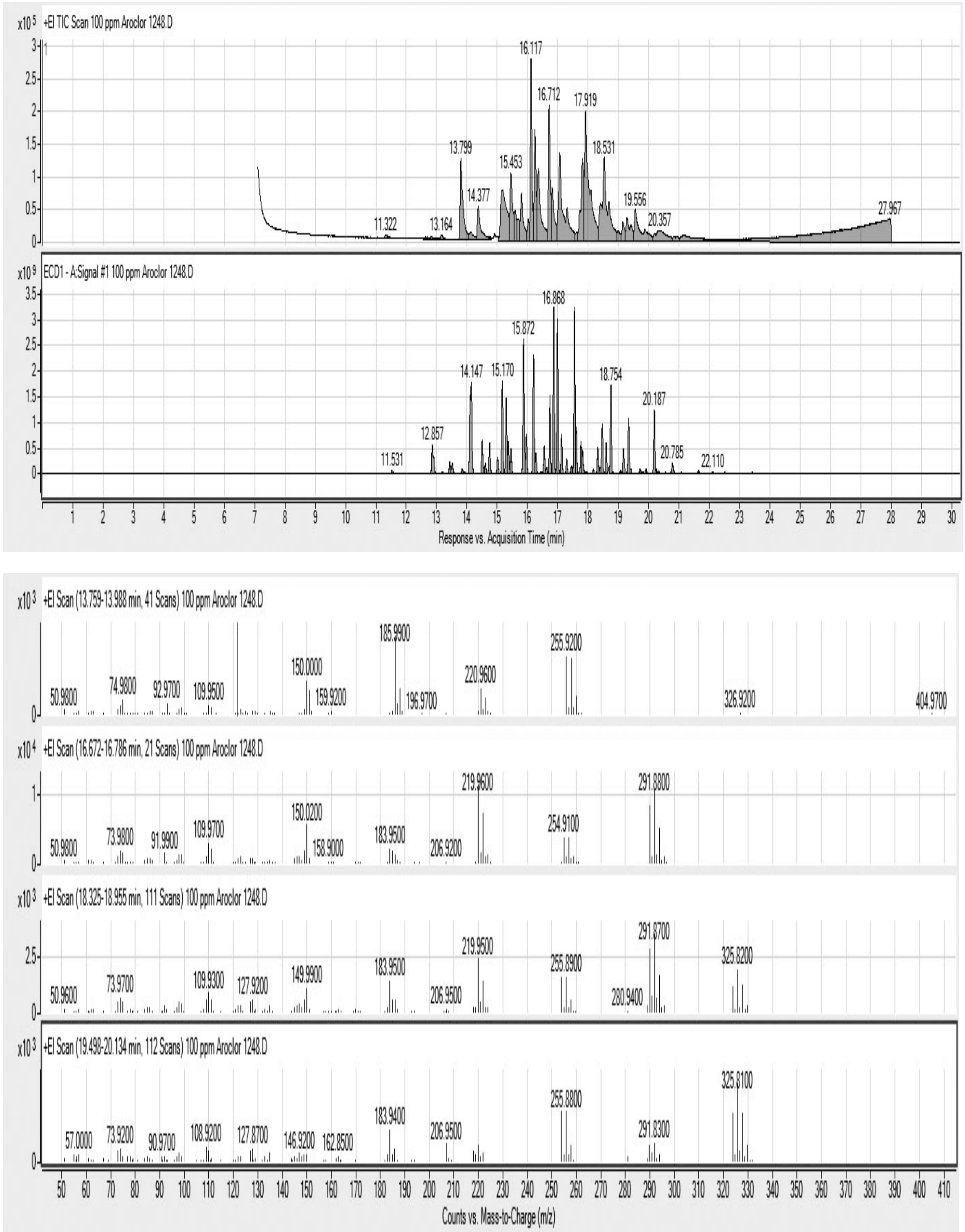

Figure 26: Aroclor 100 ppm 1248 MSD/ECD

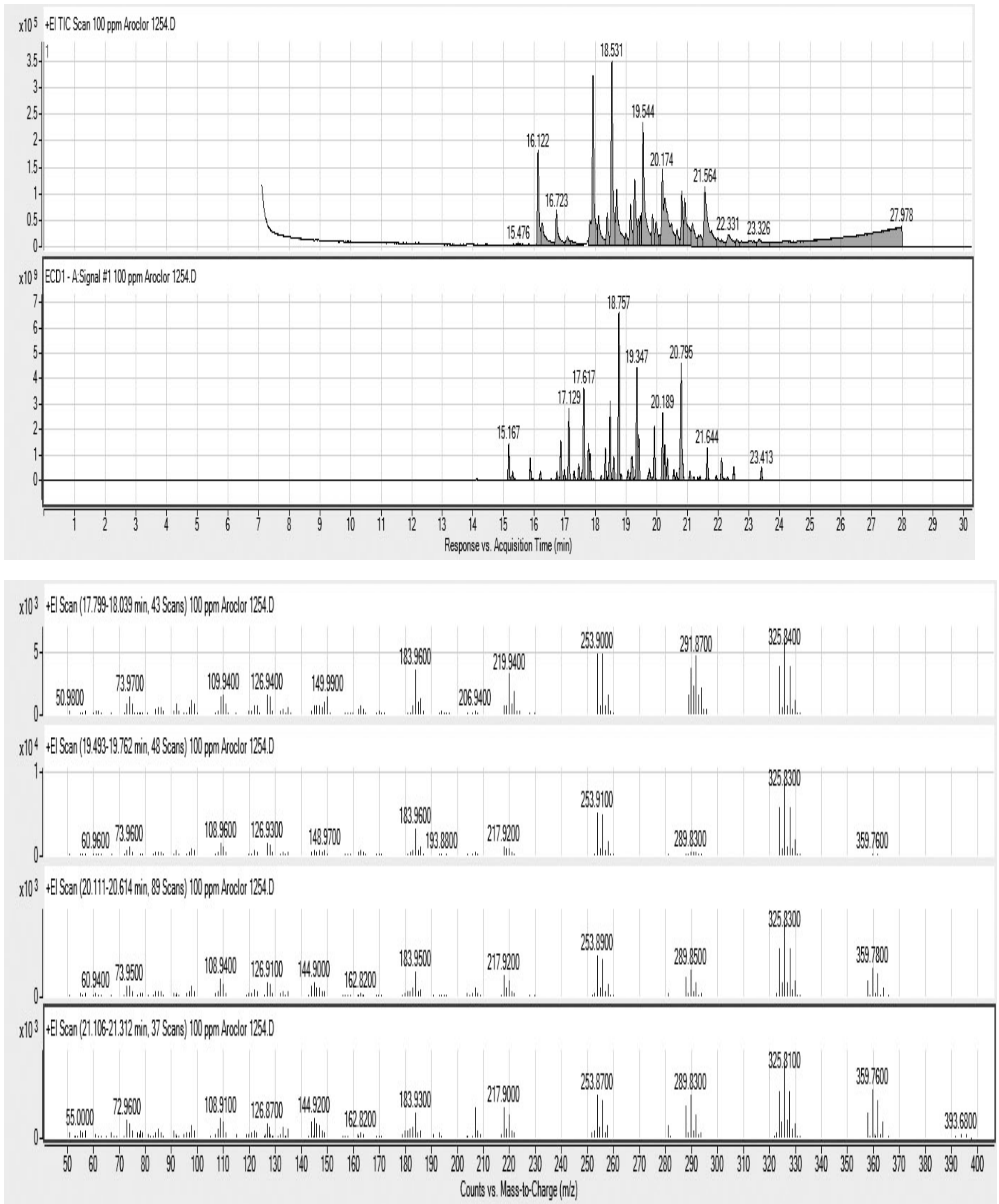

Figure 27: Aroclor 100 ppm 1254 MSD/ECD

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Gas Chromatography with Electron Capture Detector analysis can be used to establish the concentration of PCB's in random samples of transformer oil. It can be used to analyze Aroclor compounds but not individual congeners. One of the many instruments used in analytical measurement. It is very powerful in analyzing chlorinated compounds, but weak in quantifying specific congeners. The electrons emitted from ECD ionize the carrier gas eluded from GC, and the ionized gas subsequently reduces the current and is expressed as a response curve. In addition, the analysis of Aroclor commercial samples for PCBs showed ECD is very sensitive and has much better detection than MSD and it corresponds to number of chlorine molecules in the sample.

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