December 13, 2024

THIRD BRANCH
Engineering

Ms. Jian Yue, PE
Air Quality Division
Oklahoma Department of Environmental Quality
P.O. Box 1677
Oklahoma City, OK 73101-1677

Ms. Hillary Young, PE
Chief Engineer, Land Protection Division
Oklahoma Department of Environmental Quality
P.O. Box 1677
Oklahoma City, OK 73101-1677

Subject:

Reworld Tulsa RMW Permit Application, 2014-1722-TVR (M-2) Response to Air Quality Division Notice of Deficiency dated June 6, 2024

Reworld Tulsa RMW Solid Waste Permit No. 3572033 Response to Land Protection Division Notice of Deficiency dated June 27, 2024

Dear Ms. Yue and Ms. Young:

In Reworld Tulsa's response to the Notices of Deficiency dated November 27, 2024, Reworld indicated it would provide Dr. Phil Taylor's analysis of the destruction efficiency of the MWCs at the Tulsa facility. That report, along with Dr. Taylor's CV and publication list are provided herein. Please consider this submittal an addendum to the November 27, 2024 response.

Please contact me if you have any questions or would like additional information.

Yours,

Third Branch Engineering LLC

Deanne Dutton Hughes

Deanne D. Hughes, PE
Engineer

Enclosures:

- Destruction Efficiency Calculations for Monochlorobenzene, Dr. Phil Taylor, December 13, 2024
- Phil Taylor, PhD CV
- Phil Taylor, PhD Publication list

December 13, 20024

Destruction Efficiency Calculations for Monochlorobenzene

Philip H. Taylor, Ph.D.
P Taylor & Associates, LLC

1.0 Introduction

ReWorld Waste approached Dr. Phil Taylor to conduct destruction efficiency (DE) calculations for municipal waste streams containing medical waste. The Incinerability Index, developed by Dr. Taylor at the University of Dayton Research Institute with funding from the US-EPA, has been a tool for several decades to select high thermal stability surrogates for full-scale trial burn testing.[1] Monochlorobenzene (MCB) was selected for these DE calculations because it is a class 1 (most thermally stable) principal hazardous organic constituent from the Incinerability Index. The destruction efficiency (DE) for MCB was calculated for the Reworld Municipal Waste Combustor (MWC) located in Tulsa, OK. Calculations were conducted using time, temperature, waste composition, and combustion stoichiometry data provided by ReWorld for their facility in Tulsa, OK.

2.0 Background and Statement of Work

The furnace residence time and temperature were calculated by Martin GmbH ("Martin"), the original equipment manufacturer, for the Reworld municipal waste combustor located in Tulsa, OK based on temperature measurements made by Reworld employees and operational data collected in 2024 and documented in a report issued by Martin (the "Martin Report").[2] Figure 1 presents the temperature profile of the combustor for a "full load" combustion case, Model A in the Martin Report, with a thermal load of 97% based on Martin's calculations and measured temperature using an Infrared Pyrometer located 40 feet above the grate. Martin analyzed a total of 5 combustion cases labeled Models A-E. Model A was chosen for this DE analysis because it most closely reflects operation of the combustor, that is, operation of the unit at or near full thermal load firing waste having a typical heating value.

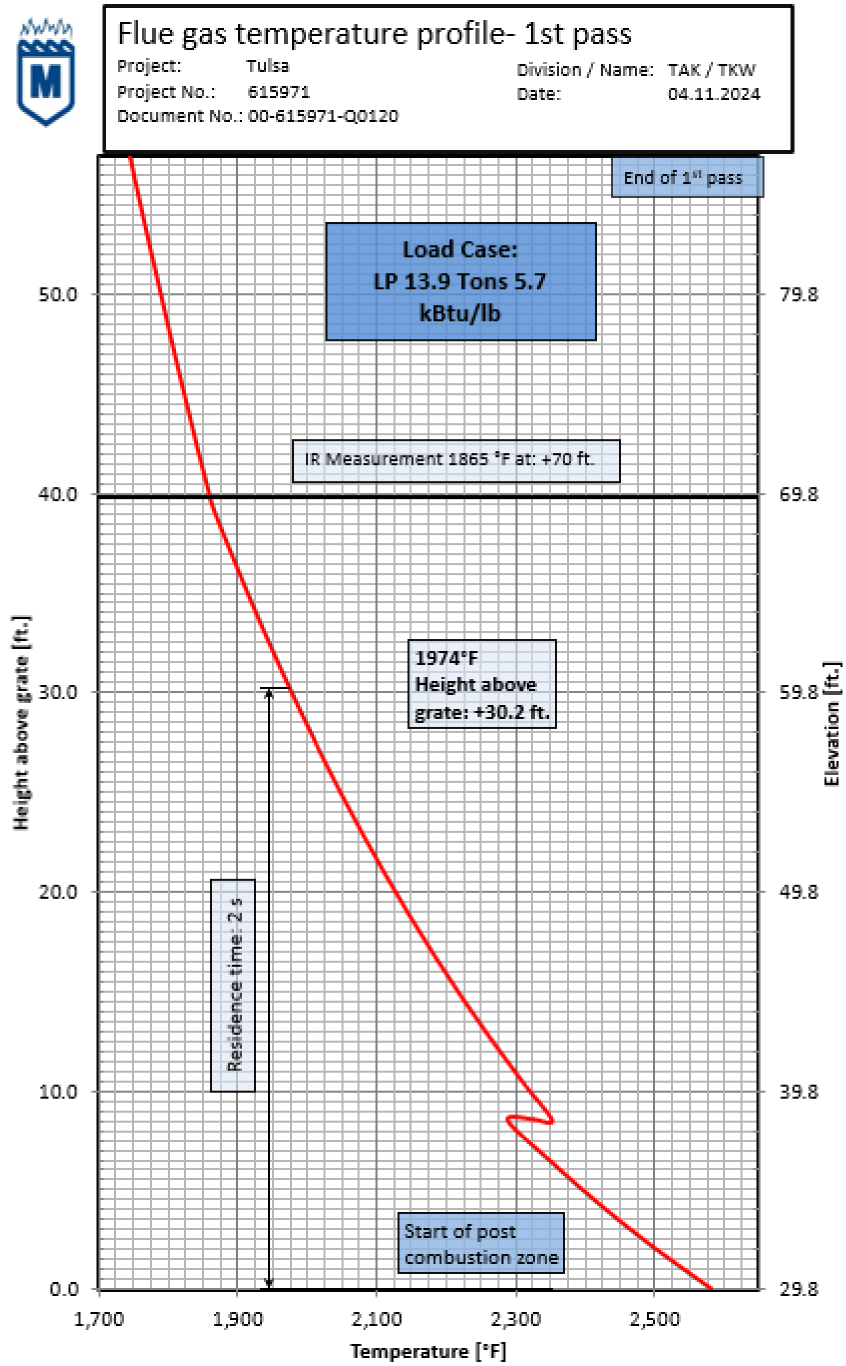

Figure 1. Furnace temperature profile with calculated flue gas temperatures at various elevations. Figure from ref. [2].

The flue gas residence time of two seconds ends 30.2 ft. above the grate

- At this height, the temperature is 1974°F
- At a temperature of 2000°F, the flue gas residence time is 1.9 s
- At a temperature of 1975°F, the residence time is 2.0 s
- At a temperature of 1800°F, the residence time is 3.4 s
- Temperature at grate level is 2584°F

3.0 Description of the Model

The destruction efficiency (DE) was calculated using the following formula:

$$DE = (1-f_r) * 100$$

where f_r $([MCB]_t/[MCB]/_0) = \exp[-(k_1+k_2[R])*t]$

The following rate constants were derived: 1) first-order thermal decomposition pathways (k_1), and 2) second-order reactions with free radicals [R] present in the combustor (k_2). t is the gas-phase residence time (sec). All calculations were performed with t = 2 sec.

Rate constants k_1 and k_2 were calculated using the Arrhenius equation:

$$k = A \exp(-Ea/(RT))$$

where A is the preexponential factor in units of 1/sec for k_1 and L / (mol -s) for k_2.

Rate constants were derived from data in the literature, as summarized by the NIST Chemical Kinetic Database.[3] Free radical concentrations were calculated using waste composition and combustion stoichiometry provided by ReWorld.

MCB is extremely stable from a theoretical combustion perspective due to the aromatic character of the molecule. The weakest bond is the C-Cl bond.[4] The dominant mode of decomposition is hydrogen abstraction by OH and H free radicals created during the combustion of the waste. The modes of attack were considered in this analysis:

- C-Cl bond fission
- H abstraction by OH radicals
- H abstraction by H radicals.

4.0 Results

The thermal destruction of MCB was calculated at a height of 30.2 ft above the grate (1974 °F). This corresponded to a gas phase residence time of 2 sec. Table 1 provides the estimated thermal destruction efficiency (DE) for MCB for these conditions.

Table 1. MCB DE Calculations

				Tulsa Facilty Aprill 2024 Base Case					
		Arrhenius Coefficients		**Kinetic Calculations**			**Destruction Efficiency**		
	Chlorobenzene	A	Ea	k (1/sec)	[MCB] t / [MCB] (	T (F)	T (K)	t (sec)	DE %)
		(1/sec) or (L/mol -sec)	(cal/mol)						
k1	C-Cl Bond Fission	3.00E+15	95600	1.052	1.22E-01	1975	1352	2.0	87.8123
k2	H Abstr. By OH	4.80E+10	6300	368.007	0.00E+00	1975	1352	2.0	99.9999+
k2	H Abstr. By H	3.00E+09	8100	20.596	1.29E-18	1975	1352	2.0	99.9999+

C-Cl bond fission (the weakest bond in MCB) is a significant decomposition pathway producing phenyl radicals and Cl atoms. However, without the presence of free radicals such as OH and H, less than 90% of MCB would be destroyed according to Table 1.

OH and H attack on the MCB aromatic ring produce chlorophenyl radicals that are unstable at these temperatures leading to destabilization of the aromatic ring (ring rupture) and the ultimate conversion of MCB to CO_2, H_2O, and HCl.

Specific observations regarding MCB DE are:

1. MCB DEs are 99.99999% (6 9's) for the baseline condition of 1,974 ˚F and 2.0 seconds,
2. The DE reported in Table 1 is only accurate to 6 decimal places following the decimal point. Hence, the DE for MCB at 1975 °F and 1832 °F is 99.9999%.

5.0 Summary

In summary, the modeling results demonstrate that MCB is predicted to be destroyed to 6 9's destruction efficiency (DE), after 2 seconds of flue gas retention time at 30.2 ft above the grate with a minimum temperature of 1832°F. This result is based on the time and temperature profiles developed by Martin based on operational data and measured temperatures at 40 feet above the grate. Temperatures and residence times of the other 4 combustion cases analyzed by Martin, 2 at 97% thermal load and 2 at 87% thermal load, were similar and would therefore predict similar destruction efficiencies of MCB. Therefore, the modeling results for destruction efficiency after 2 seconds gas residence time from this base case, Model A, are also applicable to Model B, C, D, and E.

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[1] Taylor, P.H., Dellinger B., and Lee, C.C., *Environ. Sci. Technol.* 1990, 24, 316-328.
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[3] NIST Chemical Kinetic Database, Standard Reference Database 17, Version 7.1 (Web Version), Release 1.6.8, Data Version 2024. https://kinetics.nist.gov/kinetics/
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Philip H. Taylor 12/13/24

Philip H. Taylor 12/13/24

PHILIP H. TAYLOR
1437 Spanish Moss Way, Dayton, OH 45458
(937) 430-6762 / Taylorphd6397@gmail.com

PROFESSIONAL EXPERIENCE

P Taylor & Associates LLC, Environmental Consulting
President
January 2020 – Present
Core Competencies: Grant Writing; Grant and Proposal Review; Business Capture; Proposal Preparation; Program Management; Project Management; Quality Assurance Program Plan Preparation; Water Technology Innovation Cluster Support; Hazardous Waste Incinerability; Thermal Destruction of Per- and Polyfluorinated Alkyl Substances (PFAS); Expert Witness – PFAS; Thermal Destruction of Hazardous Organic Compounds; Kinetic Modeling of Waste Destruction

Strategic Implementation, University of Cincinnati
Assistant Vice President for Research
December 2014 to December 2019
Developed and implemented programming in the following areas: research development focused on junior faculty; collaborative, cross-disciplinary team research; internal seed funding; research infrastructure; identifying and nurturing strategic initiatives into larger, self-sustaining, research centers; diversifying federally sponsored research portfolio; and facilitation and coordination of faculty engagement with industry.

University of Cincinnati
Research Director
June 2014 to November 2014
Responsible for proposal writing and research program development and increasing sponsored research funding in College of Engineering and Applied Science; worked closely with faculty and department heads, leading and coordinating proposal development, and coaching and training faculty and staff in grantsmanship

University of Dayton Research Institute
Distinguished Research Scientist
2000-2014
Center Director for five year, multi-million-dollar industry supported study investigating municipal waste combustion of fluorinated polymeric materials; directed coal combustion studies aimed at improving post-combustion mercury emission control; directed fundamental hydroxyl radical kinetic research studies; fulfilled leadership roles for the University of Dayton in the development of clean energy and water monitoring technology areas

University of Dayton Research Institute
Group Leader
1998-2014
Managed diverse group of scientists/engineers conducting environmental research; responsible for technical direction and successful execution of all research programs; financial responsibility for all research program budgets

University of Dayton Research Institute
Senior Research Scientist
1992-2000
Performed fundamental research on hazardous waste incineration and alternative fuels combustion; awarded EPA STAR designation in 1994 for pilot-scale evaluation of hazardous organic waste incinerability ranking; conducted highly cited initial study of thermal degradation of fluorinated materials and assessment of potential environmental impact

University of Dayton
Graduate Engineering Professor
1991-2014
Mentored graduate students on research projects, chaired thesis/dissertation committees, taught undergraduate/graduate classes in Electro-Optics, the Chemistry Department, and the Department of Chemical and

Materials Engineering; mentored undergraduate honors students on senior projects; reviewed graduate engineering department programs for accreditation; served on internal University of Dayton accreditation committee

University of Dayton Research Institute
Research Scientist
1985-1992
Conducted fundamental & applied research on hazardous waste incineration; awarded EPA STAR designation for development of hazardous organic waste incinerability ranking; co-investigator on fundamental research proposals including funding from National Science Foundation

National Bureau of Standards
NRC Postdoctoral Fellow
1984-85
Conducted novel laser diagnostic interrogation of diffusion flames

Penn State University
Postdoctoral Associate
1984
Conducted experimental study of pulverized wood combustion

Penn State University
Graduate Research Assistant
1980-1984
Conducted fundamental flame suppression studies for Naval Research Laboratory; completed PhD dissertation; GPA 3.71

EDUCATION AND OTHER

B.S. Chemistry, SUNY Oneonta, 1980
Ph.D. Fuel Science, Penn State University, 1984
National Research Council Postdoctoral Fellowship, 1984, 1985
US-EPA STAR Awards, 1991, 1994

Value Proposition

Leadership:

- ✓ Responsible for articulating a vision for future funding for a large multi-disciplinary group of scientists and engineers at UDRI
- ✓ Served in numerous internal and external leadership positions at the University of Dayton including University Clean Energy Alliance Board of Governors and Confluence/Water Technology Innovation Cluster Board of Directors
- ✓ Currently Assistant Vice President for Research and Executive-on-loan to Confluence/Water Technology Innovation Cluster for the Office of Research, University of Cincinnati

Management:

- ✓ Management and supervisory experience includes annual performance reviews for large multi-disciplinary group of scientists and engineers; supervised social sciences grant officer and Director of Cyber Research Initiatives for University of Cincinnati
- ✓ Responsible for technical deliverables and financial management of major, multi-year contracts and grants for both federal government and large industrial companies

Technical Skills:

- ✓ Provided technical direction for a group of 12 scientists and engineers in the field of environmental engineering
- ✓ Unique technical, organizational and people-oriented skills and experience that are applied to interdisciplinary R & D teams
- ✓ International reputation in the field hazardous waste combustion with funding from NSF, DOE, and EPA
- ✓ Center director for large, multi-year EPA directed fluorocarbon combustion study involving numerous analytical labs and industrial companies with complex contractual requirements

Strategic Planning/Program Development

- ✓ Participated in strategic planning for group, division and research institute related primarily to energy and environmental engineering research and technology development
- ✓ Identified new federal, state and industrial funding opportunities
- ✓ Prepared and successfully submitted requests for financial assistance including complex proposals involving various forms of cost sharing
- ✓ Successfully negotiated new funding contracts and grants (totaling more than $30M over the past 25+ yrs)

External Professional Association and Board Memberships

Air and Waste Management Association, Association for the Advance of Science, American Chemical Society, Sigma Xi Research Society

Chair and University representative for Board of Governors for University Clean Energy Alliance of Ohio (2011-2013). University of Dayton representative on Board of Directors for Confluence/Water Technology Innovation Cluster (2011-2013). University of Cincinnati representative on Board of Directors for Confluence/Water Technology Innovation Cluster (2016-2019).

Board and Committee Activities at the University of Cincinnati

Executive Research Advisory Board – charge was broad implementation of the President's strategic directions initiative (2017-2019)

Research Advisory Board – reviewed and approved strategies and metrics for implementing elements of strategic directions initiative

Subcommittees (3) to Research Advisory Board; development of strategies and metrics for: growth of National Academy membership; creating a culture of safe laboratory practices; and infrastructure assessment

Center for Clinical and Translational Science and Training integration Committee – provide mentoring and consultation for faculty interested in cross-disciplinary collaborations in health-related research

Chair of two Strategic Research Initiative task forces: 1) Faculty Research Career Development and 2) Cross Disciplinary Team Research

Co-chair of UC@IT Research and Development Subcommittee – charge is to identify and advance cyberinfrastructure needs including centralized Advanced Research Computing

Additional Information

- ✓ 60+ peer-reviewed journal publications and 100+ technical presentations at national and international conferences and symposia (see following pages)
- ✓ Principal or co-principal investigator on over 30 government and commercial grants, contracts and subcontracts over the past 25+ years. Total dollar value exceeds $30M
- ✓ Invited lectures at major conferences and symposia and to educational institutions and industry
- ✓ Scientific grant reviewer for federal agencies including NSF, EPA, DOE and NIH
- ✓ Small Business Innovative Research reviewer for EPA and NSF

JOURNAL PUBLICATIONS

63. H-J Gehrmann, P. Taylor, K. Aleksandrov, P. Bergdolt, A. Bologa, D. Blye, P. Dalal, P. Gunasekar, S. Herremanns, D. Kapoor, M. Michell, V. Nuredin, M. Schlipf, D. Stapf, Mineralization of Fluoropolymers from Combustion in a Pilot Plant under Representative European Municipal and Hazardous Waste Combustor Conditions, **Chemosphere**, 365, 143403, 2024. https://doi.org/10.1016/j.chemosphere.2024.143403.

62. K. Weitz, D. Kantner, A. Kessler, H. Key, J. Larson, W. Bodnar, S. Parvathikar, L. Davis, N. Robey, P. Taylor, F. De la Cruz, T. Tolaymat, W. Linak, . Krug, L. Phelps, A Critical Review of Perfluoroalkyl and Polyfluoroalkyl Substances in Thermal Waste Treatment Systems in the United States, **Science Total Environment.**, 932, 172658, 2024. https://doi.org/10.1016/j.scitotenv.2024.172658

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60. R. J. Giraud, Taylor, P. H., and Huang, C-p., Combustion Operating Conditions for Municipal and Medical Waste Incinerators in the U.S., **Waste Management**, 132, 124, 2021.

59. P. H. Taylor, T. Yamada, R. C. Striebich, J. L. Graham, and R. J. Giraud, Investigation of Waste Incineration of Fluorotelomer-based Polymers as a Potential Source of PFOA in the Environment, **Chemosphere**, 110, 17, 2014

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56. P. H. Taylor, T. Yamada, and P. Marshall, "The Reaction of OH with Acetaldehyde and Deuterated Acetaldehyde: Further Insight into the Reaction Mechanism at both Low and Elevated Temperatures" **Int. J. Chem. Kinet.**, 38, 489, 2006.

55. R. Ananthula, T. Yamada, and P. H. Taylor, Kinetics of OH Radical Reaction with Anthracene and Anthracene-d_{10}, **J. Phys. Chem. A**, 110, 3559, 2006.

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53. P. H. Taylor, R, Mallipeddi, and T. Yamada, "LP/LIF Study of the Formation and Consumption of Mercury (I) Chloride: Kinetics of Mercury Chlorination," **Chemosphere** 61, 685, 2005.

52. P. H. Taylor, T. Yamada, and A. J. Neuforth, "Kinetics of OH Radical Reactions with Dibenzo-p-dioxin and Selected Chlorinated Dibenzo-p-dioxins," **Chemosphere**, 58, 243, 2004.

51. T. Yamada, P. H. Taylor, A. Goumri, and P. Marshall, "The Reaction of OH with Acetone and Acetone-d_6 from 298 to 832 K: Rate Coefficients and Mechanism," **J. Chem. Phys.** 119, 10600, 2003.

50. T. Yamada, M. Siraj, and P. H. Taylor, J. Peng, X. Hu and P. Marshall, "Rate Coefficients and Mechanistic Analysis for Reaction of OH with Vinyl Chloride between 292 and 730 K," **J. Phys. Chem. A**, 105, 9436, 2001.

49. T. Yamada, A. El-Sinawi, M. Siraj, and P. H. Taylor, J. Peng, X. Hu and P. Marshall, Rate Coefficients and Mechanistic Analysis for Reaction of OH with 1,1-Dichloroethene and *trans*-1,2-Dichloroethene over an Extended Temperature Range, **J. Phys. Chem. A**, 105, 7588, 2001.

48. P. H. Taylor and D. Lenoir, "Chloroaromatic Formation in Incineration Processes," **Science Total Environ.**, 269, 1, 2001.

47. D. Lenoir, A. Wehrmeier, S. S. Sidhu, P. H. Taylor, "Formation and Inhibition of Chloroaromatic Micropollutants formed in Incineration Processes," **Chemosphere**, 43, 107, 2001.

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41. T. D. Fang, P. H. Taylor, and R. J. Berry, "Kinetics of the Reaction of OH Radicals with CH_2ClCF_2Cl and CH_2ClCF_3 over an Extended Temperature Range," **J. Phys. Chem. A**, 103, 2700, 1999.

40. P. H. Taylor and B. Dellinger, “Pyrolysis and Molecular Growth of Chlorinated Hydrocarbons,” **J. Anal. Appl. Pyrol.**, 49, 9, 1999.

39. P. H. Taylor, S. Shanbhag, W. A. Rubey, B. Dellinger, and M. Bergin, “Speciation of Organic By-Products from the Thermal Decomposition of Alternative Automotive Fuels,” **Air Waste Manage. Assoc. J.**, 49, 39, 1999.

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37. A. Wehrmeier, D. Lenoir, S. S. Sidhu, P. H. Taylor, W. A. Rubey, A. Kettrup, and B. Dellinger, “The Role of Copper Species in Chlorination and Condensation Reactions of Acetylene,” **Environ. Sci. Technol.**, 32, 2741, 1998.

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35. P. H. Taylor, L. Cheng, and B. Dellinger, “The Influence of Nitric Oxide on the Oxidation of Methanol and Ethanol,” **Combust. Flame**, 115, 562, 1998.

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25. P. H. Taylor, D. A. Tirey, and B. Dellinger, "A Comprehensive Kinetic Model of the High Temperature Pyrolysis of Tetrachloroethene," **Combust. Flame**, 104, 260, 1996.

24. P. H. Taylor, S. Shanbhag, and B. Dellinger, "The High-Temperature Pyrolysis and Oxidation of Methanol and Ethanol: Experimental Results and Comparison with Vehicle Emission Tests," in **Progress in Emission Control Technologies (SP-1053)**, SAE Technical Paper Series #941904, p. 39, Warrendale, PA, 1994.

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22. Z. Jiang, P. H. Taylor, and B. Dellinger, "LP/LIF Studies of the Reaction of OH with 1,1,1,2- and 1,1,2,2-Tetrachloroethane Over an Extended Temperature Range," **J. Phys. Chem.**, 97, 5050, 1993.

21. P. H. Taylor, Z. Jiang, and B. Dellinger, "Determination of the Gas-Phase Reactivity of Hydroxyl with Chlorinated Methanes at High Temperature-Effects of Laser/Thermal Photochemistry," **Int. J. Chem. Kinet.**, 25, 9, 1993.

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19. Z. Jiang, P. H. Taylor, and B. Dellinger, "LP-LIF Studies of the Reaction of OH with 1,1,1-Trichloroethane Over an Extended Temperature Range," **J. Phys. Chem.**, 96, 8961, 1992.

18. Z. Jiang, P. H. Taylor, and B. Dellinger, "LP-LIF Studies of the Reaction of OH with 1,1-Dichloroethane Over an Extended Temperature Range," **J. Phys. Chem.**, 96, 8964, 1992.

17. G. J. Carroll, R. C. Thurnau, J. W. Lee, L. R. Waterland, B. Dellinger, and P. H. Taylor, "Pilot-Scale Evaluation of an Incinerability Ranking System for Hazardous Organic Compounds," **J. Air Waste Manage. Assoc.**, 42, 1430, 1992.

16. P. H. Taylor, Z. Jiang, and B. Dellinger, "Laser Photolysis/Laser Induced Fluorescence Studies of the Reaction of Hydroxyl with 1,1,2-Trichloroethane Over an Extended Temperature Range," **J. Phys. Chem.**, 96, 1293, 1992.

15. P. H. Taylor, S. McCarron, and B. Dellinger, "Investigation of 1,2-Dichloroethane-Hydroxyl Kinetics over an Extended Temperature Range: Effect of Chlorine Substitution," **Chem. Phys. Lett.**, 177, 27, 1991.

14. P. H. Taylor, B. Dellinger, and D. A. Tirey, "Oxidative Pyrolysis of CH_2Cl_2, $CHCl_3$, and CCl_4-I: Incineration Implications," **Int. J. Chem. Kinet.**, 23, 1051, 1991.

13. D. A. Tirey, P. H. Taylor, and B. Dellinger, "Products of Incomplete Combustion from the High Temperature Pyrolysis of the Chlorinated Methanes," in **Emissions from Combustion Processes: Origin, Measurement, and Control**, Chapter 8, p. 109, 1990.

12. D. A. Tirey, P. H. Taylor, J. H. Kasner, and B. Dellinger, "Gas Phase Formation of Chlorinated Aromatic Compounds from the Pyrolysis of Tetrachloroethylene," **Combust. Sci. Technol.**, 74, 137, 1990.

11. J. H. Kasner, P. H. Taylor, and B. Dellinger, "Laser Photolysis/Laser-Induced Fluorescence Study of OH-C_2H_5Cl Rate Constants from 294-789 K," **J. Phys. Chem.**, 94, 3250, 1990.

10. P. H. Taylor, B. Dellinger, and C. C. Lee, "Development of a Thermal Stability-Based Ranking of Hazardous Organic Compound Incinerability," **Environ. Sci. Technol.**, 24, 316, 1990.

9. B. Dellinger, P. H. Taylor, D. A. Tirey, and C. C. Lee, "Pathways of Formation of Chlorinated PICs from the Thermal Degradation of Simple Chlorinated Hydrocarbons," **J. Hazard. Mater.**, 22, 175, 1989.

8. P. H. Taylor, J. A. D'Angelo, M. C. Martin, J. H. Kasner, and B. Dellinger, "Laser Photolysis/Laser Induced Fluorescence Studies of Reaction Rates of OH with CH_3Cl, CH_2Cl_2, and $CHCl_3$ Over an Extended Temperature Range," **Int. J. Chem. Kinet.**, 21, 829, 1989.

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