TECHNICAL REPORT
Project ID #0003018009 VOLUME III

THERMOPHYSICAL AND FIRE PROPERTIES OF AUTOMOBILE PLASTIC PARTS AND ENGINE COMPARTMENT FLUIDS

By
A. Tewarson, FM Global, Norwood, MA, USA

Prepared for
Motor Vehicle Fire Research Institute
Attention: Ken Digges, President
1334 Pendleton Court
Charlottesville, VA, USA

October 2005

TECHNICAL REPORT #0003018009, VOLUME III

THERMOPHYSICAL AND FIRE PROPERTIES OF AUTOMOBILE PLASTIC PARTS AND ENGINE COMPARTMENT FLUIDS

By:
A. Tewarson
FM Global
Norwood, MA, USA

Prepared for:
Motor Vehicle Fire Research Institute
Attention: Ken Digges, President
1334 Pendleton Court
Charlottesville, VA, USA

October 2005

Project ID 0003018009-3

Approved by:
Robert G. Bill, Jr.

Robert G. Bill, Jr.
Assistant Vice President and Director
Measurements and Models Research

DISCLAIMER

ABSTRACT

Data for the thermophysical and fire properties of plastic parts from two vehicles (1996 Dodge Caravan- about 73 parts and 1997 Chevrolet Camaro- about 122 parts) and engine compartment fluids (hydrocarbon fluids- 16 new and 25 used, glycol fluids- five new and one used, and alcohols- two new and two used) are presented. All the data were measured following 12 different ASTM Standard Test Protocols, a hot surface ignition temperature apparatus developed by GM, and by slightly modifying the ASTM E2058 FPA test procedure for the fluids.

The thermophysical and fire properties of plastic parts and engine compartment fluids show good correlations and provide information for the usefulness of the properties as inputs to models or tools to assess hazards and passenger survivability in vehicle crash fires.

Flame spread is one of the key behaviors specified for the acceptance criterion of plastics for vehicle parts in the FMVSS 571.302 standard, which is NHTSA's regulatory standard test designed to simulate ignition by a burning cigarette or a match in the passenger compartment. However, plastic parts, which pass the FMVSS 571.302 standard test requirement, are found to have rapid flame spread in the ASTM E2058 FPA flame spread test, where large-scale flame heat flux conditions, typical of vehicle crash fires, are simulated. Therefore, it is recommended that a fire propagation index (**FPI**) ≤ 10 $(\mathrm{m/s}^{1/2})/(\mathrm{kW/m})^{2/3}$ be used as a criterion for the acceptance of plastics for vehicle parts, specially at locations where flames are expected to penetrate the passenger compartment. A standard based on **FPI** already exists for the acceptance of plastics for clean rooms of the semi-conductor industry (ANSI/FM 4910, NFPA 287), which can be adopted for the acceptance of plastics for vehicle parts. The standard could also include an acceptance criterion of plastics based on smoke yield ≤ 0.06 g/g (smoke yield for most common plastics used in the automobile parts, such as polyethylene, polypropylene, and nylon). Since smoke and CO yields are interrelated (Appendix A-4), plastic acceptance criterion for smoke would also specify plastic acceptance criterion for CO.

The initial and final boiling points of the engine compartment fluids, which are related to the flash point, autoignition temperature and hot surface ignition temperature of the fluids, are useful parameters for the hazard classification of the fluids.

All the reports generated in the studies sponsored by GM are listed in the NHTSA web page (www.nhtsa.dot.gov) and studies sponsored by NHTSA, and MVFRI in the MVFRI web page (www.mvfri.org).

ACKNOWLEDGMENTS

Continued encouragements and technical support from Dr. K. H. Digges and Dr. R. R. Stephenson of the Motor Vehicle Fire Research Institute (MVFRI) are gratefully acknowledged. We are also thankful to Ms. Cheryl McGrath and Ms. Lisa Ouellet of FM Global for painstakingly assembling various chapters of the report from three authors.

EXECUTIVE SUMMARY

Published results from the reports of the research studies sponsored by General Motor Corporation (GM), National Highway Traffic Safety Administration (NHTSA) and Motor Vehicle Fire Research Institute (MVFRI) have been reviewed to assess the passenger survivability in vehicle crash fires. The results from the review are presented in three reports:

1) Volume I: Post Collision Motor Vehicle Fires;
2) Volume II: Theory and Testing for the Fire Behavior of Materials for the Transportation Industry;
3) Volume III: Thermophysical and Fire Properties of Motor Vehicle Plastic Parts and Engine Compartment Fluids.

This volume deals with the thermophysical and fire properties of plastic parts of vehicles and engine compartment fluids and relationships between them. The plastic parts were taken from a 1996 Dodge Caravan (about 73 parts) and from a 1997 Chevrolet Camaro (about 122 parts). Both new and used engine compartment fluids from different vehicles were used. The fluids consisted of hydrocarbons (16 new and 25), glycols (five new and one used) and alcohols (two new and two used.

The thermophysical properties of plastic parts measured were: chemical composition, melting point ($\mathbf{T_m}$), glass transition temperature ($\mathbf{T_{glass}}$), heat of fusion ($\mathbf{\Delta H_{fusion}}$), density ($\rho$), thermal conductivity (**k**), heat capacity ($\mathbf{c_p}$) , and temperature of vaporization or decomposition ($\mathbf{T_{v\ or\ d}}$). The fire properties of the plastic parts measured consisted of critical heat flux (**CHF**) and thermal response parameter (**TRP**) for ignition, heat release parameter (**HRP**), fire propagation index (**FPI**), heat of combustion ($\mathbf{\Delta H_{ch}}$), and yields of products ($\mathbf{y_j}$).

The thermophysical properties of engine compartment fluids measured were: density (ρ), boiling point ($\mathbf{T_b}$), distillation temperature and fraction, heat capacity ($\mathbf{c_p}$), flash point ($\mathbf{T_{flash}}$), fire point ($\mathbf{T_{fire}}$), hot surface ignition ($\mathbf{T_{hot}}$), autoignition temperature ($\mathbf{T_a}$), upper and lower flammability limits (**UFL** and **LFL**), and heat of vaporization ($\mathbf{\Delta H_v}$). The fire properties of engine compartment fluids measured consisted $\mathbf{\Delta H_{ch}}$ and $\mathbf{y_j}$.

The thermophysical properties of plastic parts suggested that most of the plastics in vehicle parts were melting type, easy to ignite with rapid flame spread and burned as high heat release rate molten plastic pool fires. It was possible to describe thermal penetration from the

surface to the interior of the plastic by the combination of thermophysical properties, $\Delta \mathbf{T}_{\mathbf{v\,or\,d}}\sqrt{\pi \mathbf{k} \rho \mathbf{c}_{\mathbf{p}} / \mathbf{4}}$, defined as **TRP**, which agreed well the **TRP** value determined from the measured data for time-to-ignition at various external heat flux values (ignition tests).

Flame spread rate was measured in the FMVSS 571.302 standard test, GM modified 9833P test and in the ASTM E2058 FPA. The heat exposure to the sample surface was lowest in the FMVSS 571.302 standard test (simulates burning cigarette or match in the passenger compartment), intermediate in the GM modified 9833P test and highest in the ASTM E2058 FPA test (typical heat flux expected in the motor vehicle crash fires). Thus, flame spread rate measured in the FMVSS 571.302 standard test, was lowest and did not agree with the rate measured in the GM modified 9833P test, where plastic surface was heated to 121 ^{o}C. The flame spread rates from these two tests did not agree with the rate measured in the ASTM E2058 FPA (expected flame spread behavior based on the **FPI** value determined from the data measured under simulated large-scale heat flux values, typical of vehicle crash fires).

For majority of the plastic parts from a 1996 Dodge Caravan and 1997 Chevrolet Camaro, the **FPI** values are greater than 11 $(m/s^{1/2})/(kW/m)^{2/3}$. For plastics with **FPI** values ≤ 6 $(m/s^{1/2})/(kW/m)^{2/3}$, there is no flame spread beyond the ignition zone. For plastics with **FPI** values > 6 $(m/s^{1/2})/(kW/m)^{2/3}$ but ≤ 10 $(m/s^{1/2})/(kW/m)^{2/3}$, flame spread is either limited to the ignition zone or there is a very slow flame spread beyond the ignition. Therefore, it is recommended that **FPI** ≤ 10 $(m/s^{1/2})/(kW/m)^{2/3}$ be used as a criterion for the acceptance of plastics for vehicle parts, specially at locations where flames are expected to penetrate the passenger compartment. It would be easy to adopt the **FPI** based standard as a standard already exists for the acceptance of plastics for clean rooms of the semi-conductor industry (ANSI/FM 4910, NFPA 287). The standard could also include an acceptance criterion of plastics based on smoke yield ≤ 0.06 g/g (smoke yield for most common plastics used in the automobile parts, such as polyethylene, polypropylene, and nylon). Since smoke and CO yields are interrelated (Appendix A-4), plastic acceptance criterion for smoke would also specify plastic acceptance criterion for CO.

The measured data for the engine compartment fluids show that the flash point of a fluid ≈ 0.63 x initial boiling point; autoignition temperature ≈ 0.63 x final boiling point, and hot surface ignition temperature ≈ 0.54 x final boiling point. Thus, initial and final boiling points, which are related to the flash point, autoignition temperature and hot surface ignition temperature, are useful parameters for the classification of the fluids.

This volume has been organized in two chapters and seven appendices (four for plastic parts and three for the engine compartment fluids) as follows:

Chapter I	Thermophysical and Fire Properties of Vehicle Plastic Parts;
Chapter II	Thermophysical and Fire Properties of Engine Compartment Fluids;
Appendix A-1	Vehicle Parts and Their Compositions;
Appendix A-2	Mini-Scale Test Data for Plastic Parts;
Appendix A-3	Small-Scale Test Methods for Plastic Parts;
Appendix A-4	Small-Scale Test Data for Plastic Parts;
Appendix B-1	Test Methods Used in the Quantification of the Engine Compartment Fluid Properties;
Appendix B-2	Thermophysical and Fire Property Data from the Literature and their Relationships for Fluids;
Appendix B-3	Engine Compartment Fluids Examined and Their Thermophysical and Fire Properties.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

THERMOPHYSICAL AND FIRE PROPERTIES OF VEHICLE PLASTICS PARTS

1.1 INTRODUCTION

The non-metallic parts of vehicles are made from plastics that are inherently flammable and contribute to vehicle fires, especially in crashes. Thus, for the assessment of hazards to passengers by burning plastics in motor vehicle crash fires, data are needed for their thermophysical and fire properties. Because of this need, thermophysical and fire properties of plastics used in vehicles have been quantified using mini-scale and small-scale tests in the studies sponsored by General Motors (GM), Motor Vehicle Fire Research Institute (MVFRI), and National Highway Safety Traffic Administration (NHTSA).

The motor vehicle plastic parts selected for the quantification of the properties were taken from a 1996 Dodge Caravan and from a 1997 Chevrolet Camaro. These parts are listed in Appendix A-1 in Tables A-1-1 to A-1-7. Base plastics in the selected parts from a 1997 Ford Explorer model were also identified (Table A-1-6), but their properties were not quantified.

1.2 THERMOPHYSICAL PROPERTIES

Thermophysical properties were measured using mini-scale tests, performed by GM and the Southwest Research Institute (SwRI) [1,2,3,4,5,6,7,8]. In the tests, standard thermo-analytical instruments were used with sample masses in the range of less than 1 mg to 15 mg. The instruments used were Fourier Transform Infrared Spectrometer (FTIR), X-ray Fluorescence Spectroscope, Thermal Gravimetric Analyzer (TGA), Modulated Differential Scanning Calorimeter (MDSC), Gas Chromatograph (GC), Mass Spectrometer (MS), microscope, and precision weighing balances.

The samples used were from a 1996 Dodge Caravan (about 73 parts) and from a 1997 Chevrolet Camaro (about 122 parts). Measurements were made for the following thermophysical properties:

- Chemical composition (generic nature/type and amount of the fire retardant and inert filler);
- Melting point, glass transition temperature and heat of fusion;
- Density, thermal conductivity, and heat capacity;
- Temperature of vaporization or decomposition.

The measured thermophysical data of the plastics in vehicle parts are listed in Tables A-2-1 to A-2-11 in Appendix A-2.

1.2.1 Chemical Composition

Plastics and additives in various parts of the 1996 Dodge Caravan and the 1997 Chevrolet Camaro used in the tests are listed in Appendix A-1. Data in these tables show that polyurethane, polyethylene, polypropylene and nylon are the most common plastics in the parts of these two vehicles.

There are significant variations in the amounts of inorganic fillers in the plastic parts of the two vehicles. The amounts of organic fillers in the 1996 Dodge plastic parts are smaller and are of lower variability than those in the 1997 Camaro plastic parts. Since fire resistance of plastics increases with increase in the amounts of inorganic fillers and decrease in the amounts of the organic fillers and these amounts are sufficient to modify the fire behaviors of the plastics, then differences are expected in the burn tests for the two vehicles.

1.2.2 Glass Transition, Melting and Fusion

As a plastic (thermoplastic or elastomer) is heated, it undergoes softening and melting leading to the formation of plastic melt. The plastic melt either flows away from the heat source, drips as burning molten drops (possibly igniting other materials in close proximity), or collects and burns as a liquid pool fire (one of the most hazardous conditions in a fire).

The softening, melting, and flow of plastic melt depend on the plastic morphology, (amorphous and crystalline nature of the plastic) [9]. Amorphous plastics lack sufficient regularity in packing of the chains compared to the crystalline plastics. Amorphous plastics generally exist as hard, rigid and glassy below their glass-transition temperature ($\mathbf{T_{glass}}$)[1] and as soft, flexible, rubbery materials above the glass transition temperature [9]. The density of a plastic (ρ) increases with its degree of crystallinity and is related to the physical and mechanical properties of the plastics [9]. Properties dependent on the crystallinity (e.g. stiffness, tear strength, hardness, chemical resistance, softening temperature, yield point) tend to increase with increasing density for many plastics [9].

---

[1] Glass transition temperature is the lowest temperature at which a plastic can be considered softened and possibly flowable [9].

The softening, melting, and flow of plastic are generally characterized by $\mathbf{T_{glass}}$, the melting point ($\mathbf{T_m}$)[2] and the heat of fusion ($\mathbf{\Delta H_{fusion}}$). $\mathbf{T_{glass}}$ is the property of the amorphous region, whereas $\mathbf{T_m}$ is the property of the crystalline region. The thermophysical properties quantified in the studies sponsored by GM and NHTSA are listed in Appendix A-2 in Tables A-2-1 to A-2-4. Some of the properties show that several plastics are amorphous in nature.

There are significant variations in the $\mathbf{T_{glass}}$, $\mathbf{T_m}$ and $\mathbf{\Delta H_{fusion}}$ values for the plastics and thus these plastics are expected to have different behaviors in crash fires. For example, the $\mathbf{T_{glass}}$, $\mathbf{T_m}$ and $\mathbf{\Delta H_{fusion}}$ values for many plastics are low, indicating high tendency to form flowing and dripping plastic melts and pooling as the plastics are heated in a crash fire. In the vehicle burn tests and in the tests for the vehicle parts, plastic parts with low $\mathbf{T_{glass}}$, $\mathbf{T_m}$ and $\mathbf{\Delta H_{fusion}}$ values were found to burn as pool fires of the molten plastics, which strongly affected the fires because of their increasing burning intensities. Fire retardants are found to be effective in decreasing the dripping tendencies of the plastics only at low heat exposure as indicated by the data in Table 1-1.

Table 1-1. Selected Data for Melting, Decomposition or Vaporization for Polypropylene and Nylon at Low Heat Exposure [10]

Temperature °C	**Property**	**PP**	**PP-1 (FR)**	**PP-2 (FR)**	**Nylon 6**	**Nylon 66 (FR)**
20	Melting (Drip %)	24.4	1.1	1.2	0.5	0.1
93		29.9	0.9	0.9	7.8	0.5
121		52.5	1.7	1.8	10.7	1.1
150		61.7	3.0	2.8	12.0	1.6
20	Decomposition or vaporization (Mass Loss %)	29.9	2.4	3.2	3.9	1.1
93		31.0	1.9	2.7	8.6	1.7
121		70.7	4.6	4.6	11.0	1.9
150		72.1	7.3	7.4	12.4	2.2

1.2.3 Decomposition or Vaporization

The decomposition or the vaporization behavior of a plastic is governed by its thermal stability, characterized by the vaporization or the decomposition temperature ($\mathbf{T_{v\ or\ d}}$) [9]. The $\mathbf{T_{v\ or\ d}}$ values are governed by the same factors as $\mathbf{T_{glass}}$ and $\mathbf{T_m}$ values, namely the chain rigidity and

---

[2] The melting point is a temperature at which the thermal energy in a solid material is just sufficient to overcome the intermolecular forces of attraction in the crystalline lattice so that the lattice breaks down and the material becomes a liquid, i.e. it melts [9].

strong inter-chain forces [9]. The values of $\mathbf{T_{v\ or\ d}}$, vaporization or decomposition rate for initial, major and secondary stages in nitrogen and air, measured for the plastic parts in the GM and NHTSA sponsored studies, are listed in Appendix A-2 in Tables A-2-5 to A-2-8.

The $\mathbf{T_{v\ or\ d}}$ values for the plastic parts of the 1996 Dodge Caravan and 1997 Chevrolet Camaro are in the range of 240 to 572 ^{o}C, compared with the values in the range of 270 to 789 ^{o}C for other generic plastics [11]. Plastics with $\mathbf{T_{v\ or\ d}}$ values that are closer to 240 to 270 have low resistance to ignition and flame spread and high burning intensity are identified as ordinary plastics. Many plastic parts from the two vehicles belong to this category and thus would easily ignite and would have a rapid flame spread and high burning intensity.

Percent weight loss and rate in the decomposition or vaporization of the plastics were also quantified in the mini-scale tests, data for which are listed in the Tables A-2-5 to A-2-8 in Appendix A-2. An example of the data for FR treated and untreated PP and nylon are listed in Table 1-1. The data in the table indicate that the fire retardant treatment of PP and nylon reduced melting and dripping and enhanced the thermal stability of the plastics at low heat flux exposure. The effectiveness of the fire retardant treatment at higher heat flux values, typical of motor vehicle crash fires, however, is not known, as no data were measured.

1.2.4 Thermal Penetration

Various thermophysical properties are used to characterize the thermal penetration from the heated surface to the inside of the plastics. Important thermophysical properties of plastics for thermal penetration are density ($\boldsymbol{\rho}$), thermal conductivity ($\mathbf{k}$), and heat capacity ($\mathbf{c_p}$). These properties were quantified in the mini-scale tests for the motor vehicle plastics, which are listed in Appendix A-2 in Tables A-2-9 to A-2-11. The $\boldsymbol{\rho}$ and $\mathbf{k}$ values were quantified at the ambient temperature, whereas the $\mathbf{c_p}$ values were quantified in the temperature range of –50 to 200 ^{o}C.

The penetration of heat from the surface to the interior of a plastic is expressed by $\mathbf{\Delta T_{v\ or\ d}\sqrt{\pi k \rho c_p / 4}}$, which is defined as the *thermal response parameter* (**TRP**) of the plastic [12]. Plastics with high **TRP** values have high resistance to vaporization or decomposition, release of undesirable products and ignition and flame spread. The calculated **TRP** values from $\mathbf{T_{v\ or\ d}}$, $\mathbf{k}$, ρ and $\mathbf{c_p}$ values listed Tables A-2-5 to A-2-11 in Appendix A-2, are in the range of 57 to 495 kW-s$^{1/2}$/m^{2} for the plastics in the 1996 Dodge Caravan and 1997 Chevrolet Camaro parts.

The average $\sqrt{\pi k \rho c_p / 4}$ value for the samples of the plastic parts from the two vehicles is 0.778 ± 18%, which is similar in range to the average value of 0.640 ±15% for the high temperature plastics and 0.624 ±18% for the highly halogenated plastics [17]. The $\mathbf{T_{v\ or\ d}}$ values for the high temperature and highly halogenated plastics, however, are significantly higher than the values for many plastics in vehicles parts and thus their **TRP** values are high resulting in higher resistance to ignition and flame spread. These comparisons suggest that fire resistance of plastics vehicles parts can be enhanced significantly by increasing their $\mathbf{T_{v\ or\ d}}$ values.

The thermophysical properties can be utilized for the assessment of hazards in motor vehicle crash fires by constructing contours of the locations of parts made of plastics in vehicles with varying $\mathbf{T_{glass}}$, $\mathbf{T_m}$, $\mathbf{\Delta H_{fusion}}$, $\mathbf{T_{v\ or\ d}}$ and **TRP** values (see Chapter I in Volume II). These contours could provide a priori prediction for the difficult as well as easier paths for the flames to enter the passenger compartment and for the creation of untenable conditions in the passenger compartment in vehicle crash fires. However, the thermophysical properties have very limited use at this time, as no standard methodology or model exists that can utilize them to assess the survivability of passengers in vehicle crash fires.

1.3 FIRE PROPERTIES

Fire properties of plastics in parts of vehicles were measured in small-scale tests, performed by GM, National Institute of Standards and Technology (NIST), FM Global, and SwRI [8,13,14,15,16,17,18]. In the tests, plastics were taken from about 53 parts of the 1996 Dodge Caravan and the 1997 Chevrolet Camaro listed in Appendix A-1.

Fire properties of polypropylene with three different types of fire retardant treatments and nylon with four different types of fire retardant treatments were also measured. These fire-retarded plastics were considered as possible replacements plastics for vehicle parts to enhance resistance to ignition and flame spread.

The fire properties were measured following the ASTM E1354 Standard Test Method [The Cone Calorimeter, 8,18,19], the ASTM 2058 Standard Test Method [the Fire Propagation Apparatus, 12,13,14,16,17,19], IMO FTP Cod and Air Bus Industry ABD 0031 test [8], modified GM 9833P test [15] and FMVSS 571.302 Standard test [8,20]. These tests are briefly described in Appendix A-3. The following measurements were made in the tests:

1. <u>Pre-ignition</u>: softening, melting, non-melting and charring behaviors ;

2. Ignition: time-to-ignition at various external heat flux values. The measured data were used to determine the critical heat flux (**CHF**)[3] and thermal response parameter (**TRP**)[4] values;
3. Combustion: concentrations of CO, CO_2, hydrocarbons, HCl, HCN, and NO_x, optical density of smoke, mass loss rate, total mass lost, and residue. The measured data were used to determine the heat release rate, generation rates of products (CO, CO_2, hydrocarbons, and smoke), heat of combustion, yields of products, and heat release parameter (**HRP**)[5];
4. Fire propagation: flame spread rate and burn rate. From the measured heat release rate during flame spread and the **TRP** value, fire propagation index (**FPI**)[6] of the plastic was determined.

Fire property data quantified in the small-scale tests are listed in Appendix A-4 in Tables A-4-1 through A-4-18.

1.3.1 Pre-ignition: Softening, Melting, Non-Melting and Charring Behaviors

The thermal behavior of plastics from parts of the 1996 Dodge Caravan and the 1997 Chevrolet Camaro were similar to that indicated by the $\mathbf{T_{glass}}$, $\mathbf{T_m}$, $\mathbf{\Delta H_{fusion}}$, and $\mathbf{T_{v\ or\ d}}$ values from mini-scale tests.

In the FMVSS 571.302 tests, PP, PE, EPDM rubber, and PS from the 1996 Dodge Caravan and the 1997 Chevrolet Camaro parts were found to melt and burn on the floor or burn with flaming droplets, whereas PVC, POM, PET, fiberglass/polyester, nylon/phenolic binder, nylon and nylon 6 had no sustained burning (Tables A-4-1 and A-4-2). However, irrespective of thermal behaviors, all plastics passed the FMVSS 302 test.

In the ASTM E1354 Cone Calorimeter test (Table A-4-13), out of 18 plastic parts, 33% were melting types (PP and PE), 44% were softening types (PC, PS, PET, nylon 66 polyvinyl butyral and PP), 11% were non-melting types (nylon 6/phenolic binder) and 11% were charring types (EPDM rubber and PVC). In the ASTM E2058 FPA (Tables A-4-14 to A-4-17), out of 37 plastic parts examined, 35% were melting types (PP, PE, nylon 6, ABS), 32% were softening types (PP, PC, PS, PET, PU, nylon 6), 14% were non-melting types (PU, nylon 66) and 19% were charring types (PVC, EPDM, polyester, ABS/PVC).

---

[3] Critical heat flux (**CHF**) is the external heat flux value at or below which there is no ignition under quiescent airflow condition. See Chapter I in Volume II for the theory.

[4] **TRP** = $\mathbf{\Delta T_{ig}\sqrt{(\pi k \rho c_p)/4}}$, $\mathbf{\Delta T_{ig}}$ is the ignition temperature above ambient (K). See Chapter I in Volume II for the theory.

[5] **HRP** is the ratio of the heat of combustion to heat of gasification. See Chapter I in Volume II for the theory.

[6] $\mathbf{FPI = 749(\dot{Q}_{ch}/w)^{1/3}/TRP}$, $\mathbf{\dot{Q}_{ch}}$ is the chemical heat release rate (kW) and **w** is the width of the sample (m). See Chapter I in Volume II for the theory.

The fire retardant treatment of PP and nylon 66 significantly reduced their melting tendencies in the GM 9833P test (Table A-4-8). PP had higher melting tendency than nylon 66. On the other hand, nano composite in nylon 6 increased its melting tendency.

An examination of the melting, non-melting, softening and charring behaviors show that PP, PE, nylon and ABS based parts are melting types, PC, PS, PET, and PU based parts are softening types, whereas PVC, EPDM, polyester, ABS/PVC based parts are charring types. These behaviors are modified by fire retardant treatment or inert fillers.

Melting type plastics are expected to create pools of molten plastics under the burning vehicle leading to intense pool fires, rapid flame penetration into the passenger compartment and increased burning intensity of the vehicle. This type of behavior was observed in the tests for the burning of vehicle parts and in some of the full-scale vehicle burn tests. The melting, non-melting, softening and charring behaviors of the samples of plastic-based parts are not considered as important in the FMVSS 571.302 Standard, although these behaviors were observed in the tests following this Standard. For enhancing the survivability of the passengers in the motor vehicle crash fires, it is necessary to consider these behaviors. Furthermore, use of charring types of plastics in vehicle parts should be encouraged through regulatory standards, especially at critical locations, where flames are expected to enter the passenger compartment in vehicle crash fires.

1.3.2 Ignition

When a plastic is exposed to heat source of sufficient strength, energy requirements to vaporize or decompose the plastic are satisfied and a combustible or non-combustible vapor-air mixture is created near the surface of the plastic. The combustible vapor-air mixture auto-ignites or is ignited by a small flame or other heat source near the surface and a flame is established. This is defined as the ignition of the plastic (see Volume II, Chapter 1 for the theory).

The ignition resistance of plastics has been investigated in detail both experimentally and theoretically [12,21,22,23,24 and references therein]. It is well recognized that the ignition behavior of a plastic is governed by its physical thickness (**d**) relative to the thermal penetration depth (δ) [21,22,23]. The thermal penetration depth is expressed as:

$$\delta = \sqrt{\alpha \mathbf{t}} = \sqrt{(\mathbf{k} / \rho \mathbf{c}_\mathbf{p})\mathbf{t}} \tag{1}$$

where α is the thermal diffusivity of the plastic (mm/s), **t** is the heat exposure time of the plastic surface (s). For thermally thick conditions, $\delta < \mathbf{d}$ and for thermally thin conditions, $\delta > \mathbf{d}$. In general, plastic parts of vehicles are physically thick and thus in ignition tests, the following expression for thermally thick condition [12,21,22,23,24], becomes useful for data analysis:

$$\mathbf{1/t_{ig}^{1/2} = a(\dot{q}_e^{"} - \dot{q}_{cr}^{"})/(T_{ig} - T_a)\sqrt{\pi k \rho c_p / 4}} \quad (2)$$

where $\mathbf{t_{ig}}$ is the time-to-ignition(s), **a** is the plastic surface absorptivity[7], $\mathbf{\dot{q}_e^{"}}$ is the external heat flux applied to the plastic surface, $\mathbf{\dot{q}_{cr}^{"}}$ is the critical heat flux (**CHF**)[8] per unit plastic surface area (kW/m^2), $\mathbf{T_{ig}}$ is the ignition temperature (^{0}C) and $\mathbf{T_a}$ is the ambient temperature (^{o}C). The **CHF** value is related to the $\mathbf{T_{ig}}$ value[9].

Because thermally thick conditions are satisfied, the experimental data, away from the **CHF** value, show a linear relationship between $\mathbf{1/t_{ig}^{1/2}}$ and $\mathbf{\dot{q}_e^{"}}$ values and ($\mathbf{(T_{ig} - T_a)\sqrt{\pi k \rho c / 4}}$) value is determined and defined as the thermal response parameter (**TRP**). This relationship does not hold for $\mathbf{\dot{q}_e^{"}}$ values close to the **CHF** values, where thermally thin conditions prevail due to longer heating times prior to ignition. Under these conditions, a linear relationship is found between $\mathbf{1/t_{ig}}$ and $\mathbf{\dot{q}_e^{"}}$; the intercept on the x-axis is taken as the **CHF** value of the plastic.

For determining the **CHF** and **TRP** values, $\mathbf{t_{ig}}$ values are measured at various $\mathbf{\dot{q}_e^{"}}$ values in the ignition tests in the ASTM E2058 FPA apparatus and the ASTM E1354 Cone Calorimeter (Table A-4-9 in Appendix A-4). The **CHF** and **TRP** values derived from the experimental data are listed in Tables A-4-12, A-4-16 and A-4-17 in Appendix A-4. The **TRP** values from the ASTM E2058 FPA (Tables A-4-16 and A-4-17) are higher than the values from the ASTM E1354 Cone Calorimeter (Table A-4-12) as shown in Fig. 1-1. The difference may be due to surface absorptivity, as samples surfaces are coated black only in the ASTM E2058 FPA.

The **CHF** and **TRP** values of plastics in the 1996 Dodge Caravan and the 1997 Chevrolet Camaro parts are very similar, as shown in Fig. 1-2. Similarities in data are expected as similar generic plastics are used in the parts of the two models. These **TRP** values are in excellent agreement with the **TRP** values calculated from the thermophysical properties [17].

---

[7] In Eq. 2, the plastic surface absorptivity, **a,** is taken as unity, as the ignition tests are performed with sample surfaces coated black.

[8] **CHF** value is taken as the external heat flux value at which there is no ignition under quiescent airflow condition.

[9] $\mathbf{T_{ig}(^oC) \approx [(\dot{q}_{cr}^{"})^{0.25} \text{ x } 364] - 273}$, assuming heat losses mainly due to re-radiation, plastic surface acting as a black body and ambient temperature is 20 ^{o}C.

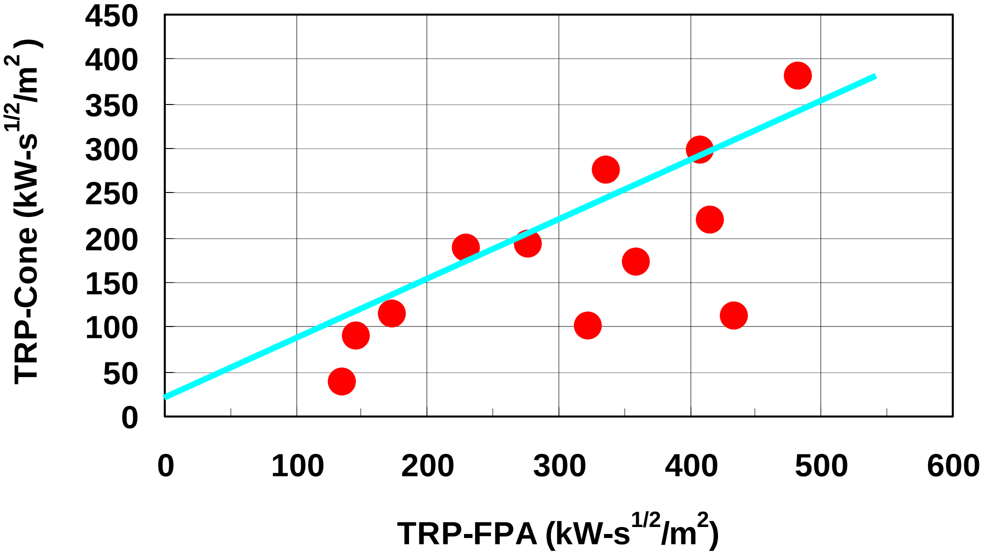


Figure 1-1 Comparison of the **TRP** values for common plastic parts of a 1996 Dodge Caravan and a 1997 Chevrolet Camaro from the ASTM E2058 FPA and ASTM E1354 Cone Calorimeter.

The **TRP** values are in the range of 39 to 483 kW-s$^{1/2}$/m^2, and the **CHF** values are in the range of 10 to 25 kW/m^2. These ranges indicate that there is wide range of resistance of the plastic parts to thermal penetration in these vehicle models. Based on the ignition, combustion and flame spread data for variety of plastics [12], plastics with **TRP** values greater than about 300 kW-s$^{1/2}$/m^2 have significant resistance to thermal penetration, increased resistance to vaporization or decomposition, ignition, flame spread and release of smoke and toxic compounds.

The **CHF** and **TRP** values provide tools to assess the effectiveness of the fire retardant treatments of plastics to enhance their fire resistance, such as for PP and nylon 66 (Table A-4-18 in Appendix A-4). These data indicate that the fire retardant treatments were ineffective in increasing the **CHF** and **TRP** values of the plastics, in agreement with the data from the burning of vehicles with fire retarded and untreated HVAC units [25]. The fire retardant treatment of HVAC was ineffective in preventing the flames to enter the passenger compartment and in reducing flame spread rates and burning intensity of the vehicle [25].

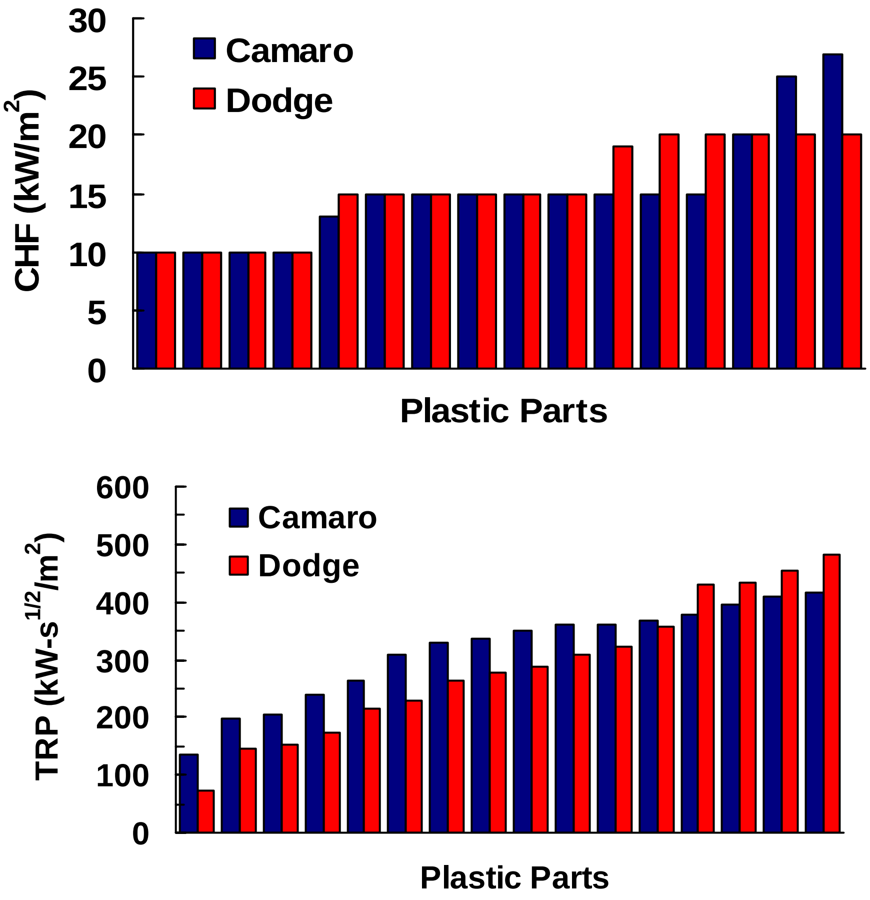


Figure 1-2. **CHF** and **TRP** values for plastic parts of a 1996 Dodge Caravan and a 1997 Chevrolet Camaro determined from the ignition data measured in the ASTM E2058 FPA [13,14,16,17].

1.3.3 Flame Spread

Flame spread process is defined as the movement of a flame on the plastic surface. The flame spread process depends on the thermophysical and fire properties of the plastics and the environmental conditions [12,21,22,23,24,26 and references therein] (see Chapter 1, Volume II for the theory).

Flame spread is specified in many standard tests, for example, the FMVSS 571.302 Standard specifies acceptance criterion for the plastics based on flame spread (less than 102 mm/min or 1.7 mm/s) in the test apparatus [20]. It is an important fire behavior associated with the hazard in a fire. In the studies sponsored by GM, flame spread was measured using two test apparatuses: 1) GM Modified 9833P Flammability Test Apparatus (Appendix A-3, Section A-3-3 [15]) and 2) ASTM E2058 FPA (Appendix A-3, Section A-3-5 [12,14,16,17]). In the study sponsored by NHTSA, the FMVSS 571.302 Standard test apparatus was used to measure the flame spread (Appendix A-3, Section A-3-1 [8]).

1.3.3.1 Flame Spread Measurements in the FMVSS 571.302 Standard Test Apparatus

The flame spread rate (burn rat) measurements were made by SwRI [8]. The data are listed in Tables A-4-1 and A-4-2 in Appendix A-4. All the parts tested satisfied the requirements of the Standard and thus passed the test.

Data show that for the PP, PE and PS based parts of the 1996 Dodge Caravan, flame spread is rapid, in the range of 20 to 68 mm/min (0.33 to 1.13 mm/s). There is no flame spread for PVC, POM, PET, and fiberglass/polyester/styrene based parts. The results are similar for the plastic parts of the 1997 Chevrolet Camaro. There is rapid flame spread for the PE and PP based parts (in the range of 15 to 37 mm/min or 0.25 to 0.62 mm/s), whereas the rate is very slow (2 mm/min or 0.03 mm/s) or there is no flame spread for nylon 6 and nylon 66 based parts.

Since the flame heat flux expected in motor vehicle crash fires are not simulated in the FMVSS 571.302 Standard Test Apparatus, the results are not representative of the flame spread behaviors of these plastics in vehicle crash fires. In vehicle crash fires, the plastic parts are expected to be exposed to higher flame heat fluxes over more extended surface areas than in the FMVSS 571.302 test.

1.3.3.2 Flame Spread Measurements in the GM Modified 9833P Flammability Test Apparatus

The flame spread rate measurements were made by GM at an environmental temperature of 121^{o}C [15]. The data are listed in Table A-4-8 in Appendix A-4. The flame spread rates for the untreated PP and nylon 6 and 66 are in the range of 54 to 149 mm/min (0.93 to 2.48 mm/s) and in the range 2.4 to 44-mm/min (0.04 to 0.73 mm/s) respectively. For fire retarded PP, the flame spread rates are in the range 4.8 to 7.2 mm/min (0.08 to 0.12 mm/s). For fire retarded nylon 66, there is no flame spread. For nylon 6 with nano composite, there is an opposite affect as the flame spread rate increases from 2.4 mm/min (0.04 mm/s) to 10.2 mm/min (0.17 mm/s), because of reduced dripping. At this low environmental temperature, there appears to be an effect of the fire retardants on the flame spread behaviors of PP, nylon 6 and nylon 66, resulting in a decrease in the flame spread rate. Reduction in the melting, however, enhances the flame spread rate.

The flame spread rate measurements at an environmental temperature of 121 ^{o}C does not simulate the environmental conditions expected in the motor vehicle crash fires. Thus, the actual flame spread rates may be quite different from the measured rates. Furthermore, the fire retardant treatments may not be as effective as indicated by the test data, as the effectiveness decreases with increase in the heat flux values. For realistic assessment of the flame spread behaviors of the plastics and effectiveness of fire retardant treatments to enhance the fire resistance, it is, therefore, necessary to perform tests with simulated flame heat flux values expected in the vehicle crash fires.

1.3.3.3 Flame Spread Measurements in the ASTM E2058 FPA

The flame spread measurements were made by FM Global using 100-mm wide, 300-mm high samples with thickness ≥ 3-mm in vertical orientations with co-flowing air having 40 % oxygen concentration and bottom of the sample exposed to 50 kW/m^2 of external heat flux in the presence of a pilot flame (Section A-3-5 Appendix A-3) [13,14,16,17]. The environment with 40% oxygen concentration was used to simulate large-scale flame radiative heat flux to plastic surfaces, expected in motor vehicle crash fires. In the test, heat release rate was measured during the flame spread on the surface of the sample. The heat release rate was combined with the **TRP** value of the plastic to determine the **FPI** value, using the following expression [12,16,17,26]:

$$\mathbf{FPI = 1000\,(0.42\,\dot{Q}'_{ch})^{1/3} = 750\ (\dot{Q}'_{ch})^{1/3}\ /\ TRP} \qquad (3)$$

FPI is in m/s$^{1/2}$)/(kW/m)$^{2/3}$, and $\mathbf{\dot{Q}'_{ch}}$ is the chemical heat release rate per unit width of the sample (kW/m). The following flame spread behaviors have been found in small-scale and large-scale tests and are consistent with the flame extinction limit [12,17,26]:

1) **FPI** ≤ 6 (m/s$^{1/2}$)/(kW/m)$^{2/3}$: no flame spread beyond the ignition zone;
2) 6 < **FPI** ≤ 10 (m/s$^{1/2}$)/(kW/m)$^{2/3}$: flame spread may or may not sustain itself beyond the ignition zone. Propagating/non-propagating flame spread behaviors can be established only in the large-scale parallel panel tests;
3) **FPI** > 10 (m/s$^{1/2}$)/(kW/m)$^{2/3}$: self-sustained flame spread beyond the ignition zone. Flame spread rate increases with increase in the **FPI** value.

The **FPI** values obtained from the flame spread tests in the ASTM E2058 FPA are listed in Table A-4-16 to A-4-18 in Appendix A-4. The **FPI** values for the plastic parts of the vehicles are plotted in Fig. 1-3. The **FPI** values for the plastic parts of the two vehicles are similar, as expected, as similar generic plastics are used in these vehicles (1996 Dodge Caravan and 1997 Chevrolet Camaro). For majority of the plastic parts, the **FPI** values are > 11 $(m/s^{1/2})/(kW/m)^{2/3}$, i.e., flame spread is expected to be self-sustained beyond the ignition zone in the vehicle crash fires. Plastics with **FPI** values ≤ 10 $(m/s^{1/2})/(kW/m)^{2/3}$ are preferred as flame spread is limited to ignition zone or there is very slow flame spread beyond the ignition zone. Thus, majority of the plastic parts in the two vehicles need only minor modifications.

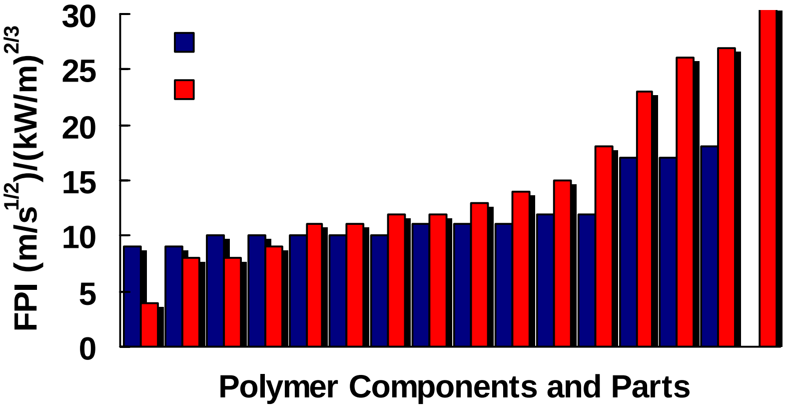


Figure 1-3. **FPI** values for plastic parts of the 1996 Dodge Caravan and the 1997 Chevrolet Camaro determined in the ASTM E2058 FPA [12,14,16,17].

An examination of the flame spread data from the FMVSS 571.302 Standard Test Apparatus (Tables A-4-1 and A-4-2 in Appendix A-4) and the **FPI** values (Tables A-4-16 and A-4-17 in Appendix A-4) indicate that there is a disagreement in the flame spread behaviors for the plastic parts. This is expected, as **FPI** values were determined in small-scale tests under simulated flame radiative heat flux expected in motor vehicle crash fires. The FMVSS 571.302 Standard Test simulates ignition of plastics in the passenger compartment exposed to a burning cigarette and a match. The FMVSS 5710.302 Standard Test thus can be complemented by specifying the **FPI** values for the acceptance of plastics for vehicle parts expected to be exposed to higher heat fluxes in vehicle crash fires.

The **FPI** values were also determined for the treated and untreated PP and nylon 6 samples (samples similar to those tested in the GM Modified 9833P Flammability Test Apparatus). The **FPI** values are listed in Table A-4-18 in Appendix A-4. An examination of the data indicates that there is hardly any difference in the **FPI** values of the treated and untreated PP and nylon and thus the FR treatment of the plastic parts is expected to be ineffective in vehicle crash fires in preventing the rapid flame spread and burning of the plastic parts. These results are in disagreement with the results from the GM Modified 9833P Flammability Test Apparatus. The disagreement is expected as **FPI** values are determined under simulated flame heat flux values expected in motor vehicle crash fires, whereas in the GM Modified 9833P Flammability Test Apparatus, flame spread rates were measured at an environmental temperature of 121 ^{o}C, which is too low to simulate the large-scale fire conditions.

One of the fire retarded PP's examined in the ASTM E2058 FPA was selected as the plastic for the HVAC unit of a vehicle [25]. This vehicle was burned along with another vehicle of the same model, but having a standard HVAC unit made of untreated PP [25]. The burn tests showed that the fire retardant treatment of PP in the HVAC was ineffective in preventing the flames to enter the passenger compartment and in reducing the flame spread rate and burning intensity. The results from the burn tests for both the vehicles were similar [25], as expected from their FPI values.

The flame spread tests in the ASTM E2058 FPA were also used to assess the melting, non-melting, softening and charring behaviors of the samples of plastic parts from the 1996 Dodge Caravan and the 1997 Chevrolet Camaro (included in Tables A-4-16 to A-4-18 in Appendix A-4). These behaviors were recorded based on the visual observations. In the determination of the **FPI** values, some of the melting type plastics created problems as the downward melting and softening rates were significantly higher than the upward flame spread rates. Thus, for these plastics, **FPI** values either were estimated or were not reported.

For the majority of the melting and softening types of plastics, the upward flame spread was very rapid compared to the downward melting and softening rates. Furthermore, heat release rate was measured until flames reached the top of the sample. However, once the flame reached the top of the sample, the downward melting and softening rates increased rapidly due to rapid penetration of heat deep into the sample. This problem was not encountered for the non-melting and charring types of plastics.

1.3.4 Combustion

The combustion process is defined in terms of the heat release rate and generation rates of products. As with the ignition and flame spread processes, the combustion process also depends on the thermophysical and fire properties of the plastics and the environmental conditions [12,21,22 and references therein]. The gas temperature and concentrations of products increase significantly above the ambient values as heat and products are released into the environment and affect the human survivability [27 and references therein] (see Chapter I, Volume II for theory).

Measurements were made for the following in the combustion tests performed in the GM, MVFRI and NHTSA sponsored studies:

- CO and HCl concentrations and yields, following the Airbus Method at 25 kW/m^2 and the IMO method at 25 and 50 kW/m^2 in flaming and non-flaming fires of the plastic parts of the 1996 Dodge Caravan by SwRI [8]. The measured data are listed in Tables A-4-3 to A-4-5 in Appendix A-4;
- Mass loss rate and release rates of heat, concentrations of CO, HCN, NO$_x$, HCl and optical density of smoke, heat of combustion and product yields using the ASTM E1354 Cone Calorimeter for the flaming fires of the plastic parts of the 1996 Dodge Caravan and the 1997 Chevrolet Camaro by SwRI [8]. The measured data are listed in Tables A-4-9 to A-4-12 in Appendix A-4;
- Mass loss rate and release rates of heat, generations rates of CO, CO$_2$, hydrocarbons and smoke, heat of combustion and yields of products using the ASTM E2058 FPA for the flaming fires of the plastic parts of the 1996 Dodge Caravan and the 1997 Chevrolet Camaro by FM Global [16,17]. The measured data are listed in Tables A-4-14 to A-4-18 in Appendix A-4.

1.3.4.1 CO Concentration Measurements by Airbus and ISO Methods

The following data were measured for the average CO yield in g/g for PC, PET and PVC based parts of the 1996 Dodge Caravan respectively (Tables A-4-3 to A-4-5 in Appendix A-4):

- Airbus Method at 25 kW/m^2 for non-flaming condition: 0.002, 0.071, and 0.011;
- Airbus Method at 25 kW/m^2 for flaming condition: 0.026, 0.082, and 0.030 ;
- IMO Method at 25 kW/m^2 for non-flaming condition: 0.001, 0.179 and 0.025;
- IMO Method at 25 kW/m^2 for flaming condition: 0.003, 0.112, and 0.004;
- IMO Method at 50 kW/m^2 for non-flaming condition: 0.074, 0.150, 0.025.

In general, CO yields from Airbus and IMO methods are similar and increase with heat flux. PET-based parts have the highest CO yields. As flame heat flux and surface areas expected in vehicle crash fires are not simulated in the tests, data are not expected to be representative of CO concentrations in vehicle crash fires.

1.3.4.2 HCl Concentration Measurements by Airbus and ISO Methods

The following data were measured for the average HCl yield in g/g as it was released from only the PVC based parts of the 1996 Dodge Caravan (Tables A-4-3 to A-4-5 in Appendix A-4):

- Airbus Method at 25 kW/m^2 for non-flaming condition: 0.027;
- Airbus Method at 25 kW/m^2 for flaming condition: 0.027 ;
- IMO Method at 25 kW/m^2 for non-flaming condition: 0.012;
- IMO Method at 25 kW/m^2 for flaming condition: 0.003;
- IMO Method at 50 kW/m^2 for non-flaming condition: 0.049.

The HCl yields are similar for the flaming and non-flaming conditions in the Airbus Method. In the IMO Method, there is a significant increase in the HCl yield with increase in the heat flux under the non-flaming condition. The HCl concentrations measured in the tests are not expected to be representative of concentrations expected in vehicle crash fires.

1.3.4.3 Measurements in the ASTM E1354 Cone Calorimeter and the ASTM E2058 FPA

- ASTM E1354 Cone Calorimeter: measurements were made for the time-to-ignition, burn time, time-to-peak heat release rate, mass loss rate, heat release rate, specific extinction area for smoke, yield of CO, HCN[10], NO_x[10] and HCl[11] and effective heat of combustion at four external heat flux values. These data are listed in Tables A-4-9, A-4-10 and A-4-11 in Appendix A-4. The specific extinction area has been converted to the yield of smoke in g/g by multiplying it by 0.0994 x 10^{-3} (see Ref. 12) and the effective heat of combustion is represented by chemical heat of combustion for consistency with the data from the ASTM E2058 FPA. The time-to-ignition has been used to determine the **CHF** and **TRP** values, which are included in Table A-4-12 in Appendix A-4.
- ASTM E2058 FPA: measurements were made for the time-to-ignition, mass loss rate, release rates of heat, and generation rates of CO, CO_2, hydrocarbons and smoke, which are listed in Tables A-4-14 and A-4-15 in Appendix A-4. The measured data were used to determine the yields of CO, CO_2, hydrocarbons and smoke, and chemical heat of combustion, which are listed in Tables A-4-17 and A-4-18 in Appendix A-4.

The combustion data for the plastic parts of the 1996 Dodge Caravan and the 1997 Chevrolet Camaro are very similar, as expected because most of them are assembled from similar generic plastics. These data comparisons for the two vehicles are shown in Figs. 1-4 and 1-5; the data were measured in the ASTM E2058 FPA [16,17]. As can be noted from the data in Tables A-4-14 and A--4-15, most of the plastic parts had large amounts of residue left at the end of their

---

[10] Released by nylon 6 and 66, as they were the only nitrogen atom containing plastics in the parts of the vehicles.
[11] Released by PVC, as it was the only halogenated plastic in the parts of the vehicle.

combustion. Some vehicle parts contain as much as 60 to 70% by weight of inert fillers. Increased amounts of inert fillers increase the fire resistance of the plastics.

The ASTM E1354 Cone Calorimeter and ASTM E2058 FPA operate under similar principles and thus many measurements made in these apparatuses are similar. However, data from these apparatus do not always agree, due to differences in the design of the apparatuses and procedures used for the measurements.

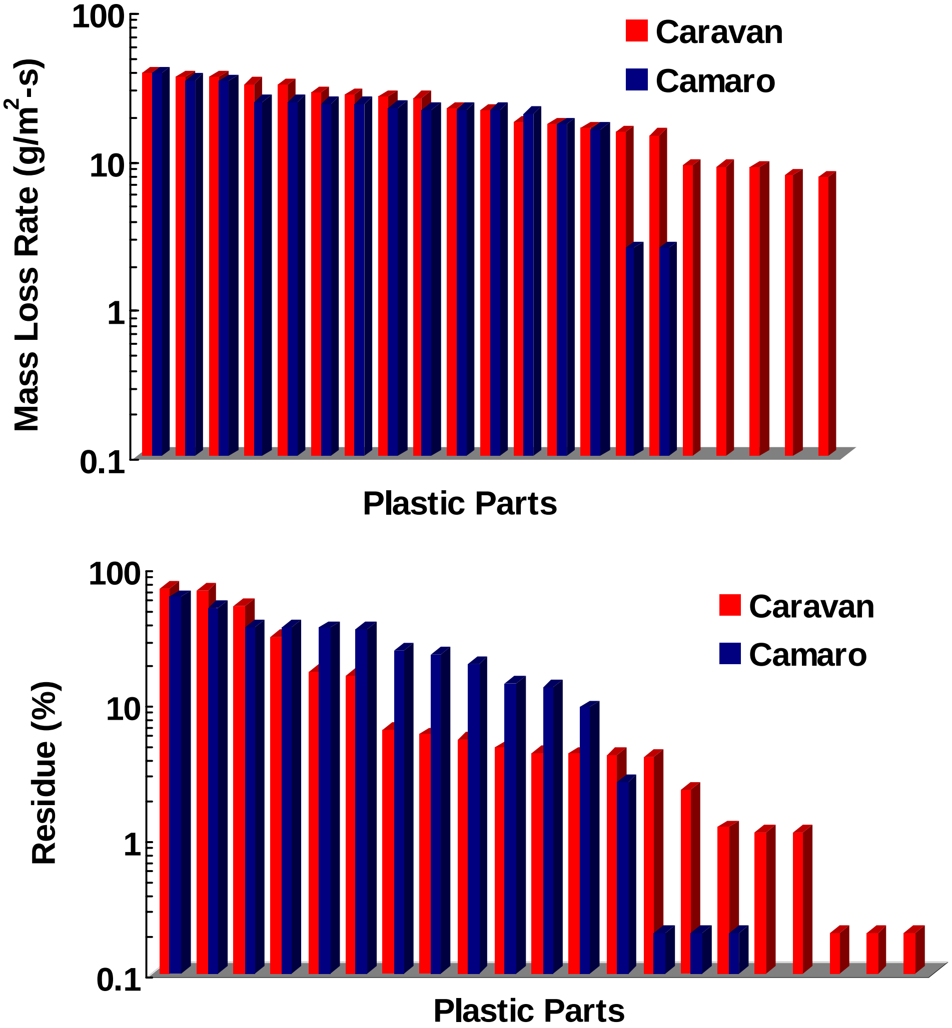


Figure 1-4. Mass loss rate and residue in the combustion of the plastic parts of the 1996 Dodge Caravan and the 1997 Chevrolet Camaro at 50 kW/m^2 in the ASTM E2058 FPA [16,17]. There were very few plastic parts for which there was no residue left after the combustion was completed, which are not shown in the figure.

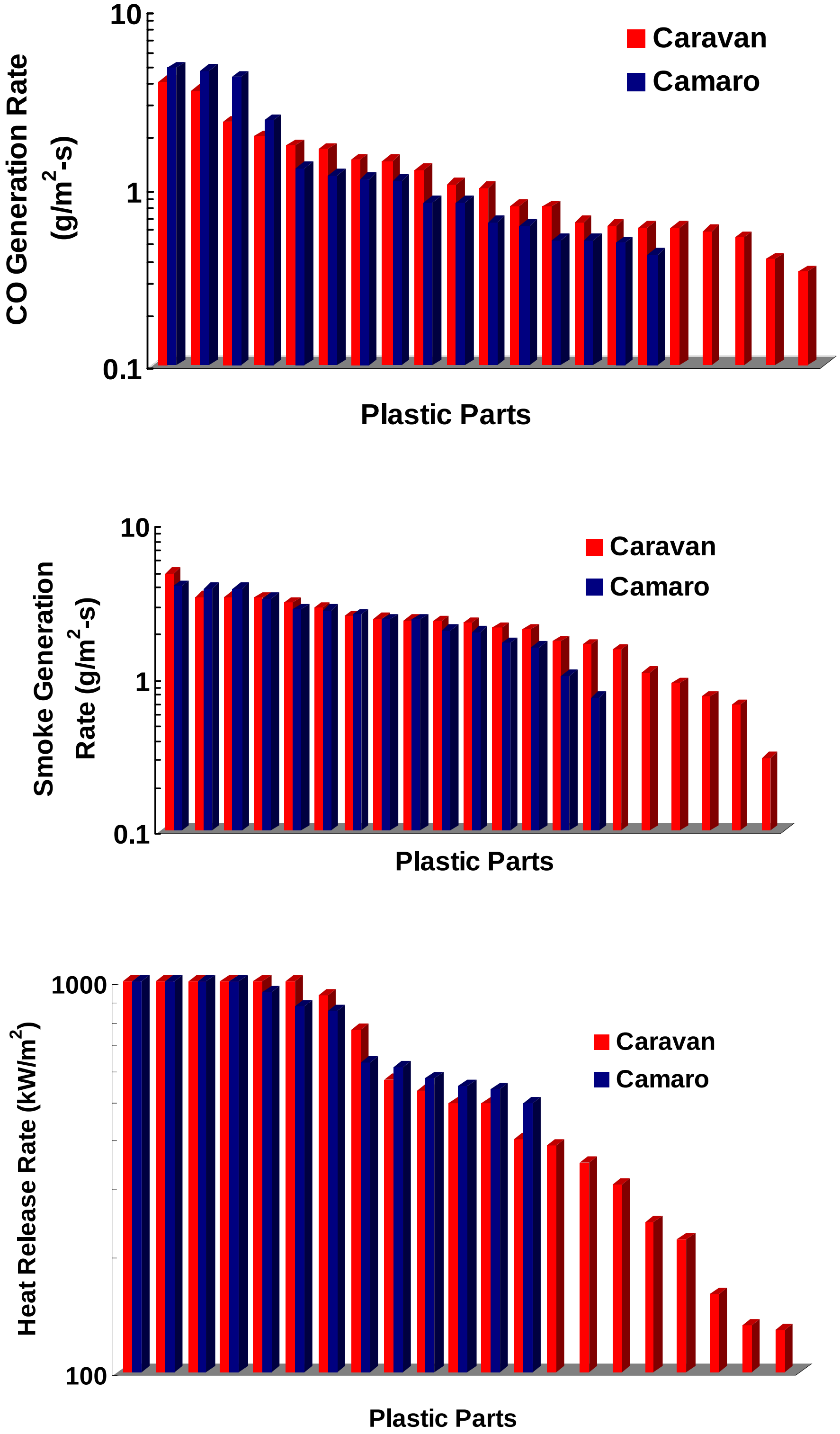


Figure 1-5 Release rates of CO, smoke, and heat from the combustion of plastic parts of the 1996 Dodge Caravan and the 1997 Chevrolet Camaro at 50 kW/m^2 in the ASTM E2058 FPA [16,17].

1.3.4.4 Comparison of Heat Release Rate from the ASTM E1354 Cone Calorimeter and the ASTM E2058 FPA

Data for the heat release rate, $\dot{Q}''_{ch}$, and heat of combustion, ΔH_{ch}, from the ASTM E1354 Cone Calorimeter and the ASTM E2058 FPA are shown in Figs. 1-6 and 1-7. There is an excellent agreement between the data from the two apparatuses for $\dot{Q}''_{ch} < 500$ kW/m^2 for charring and non melting-plastics. However, for $\dot{Q}''_{ch} > 500$ kW/m^2 for melting plastics, $\dot{Q}''_{ch}$ values from the ASTM E2058 FPA are significantly higher than from the ASTM E1354 Cone Calorimeter, although the combustion conditions are very similar as indicated by the excellent agreement between the ΔH_{ch} values in Fig. 1-7. The ΔH_{ch} values for the plastic parts of the 1996 Dodge Caravan and the 1997 Chevrolet Camaro are also in excellent agreement with the values for the similar generic plastics reported in the literature [12]

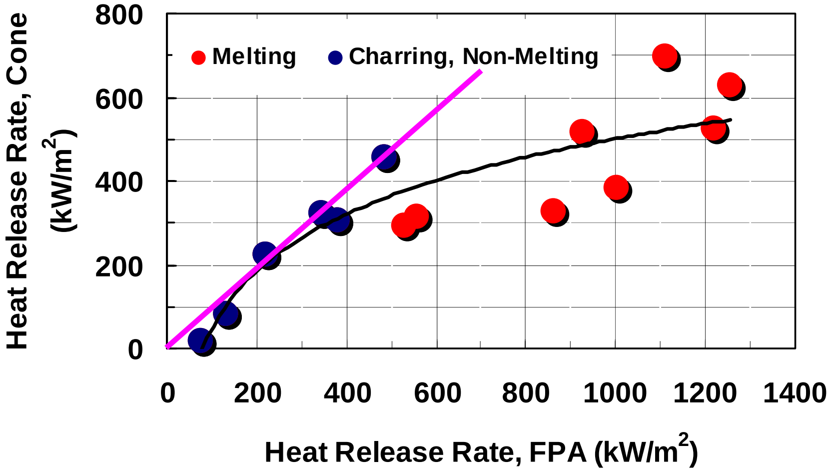


Figure 1-6. Heat release rate in the combustion of vehicle plastic parts measured at 50 kW/m^2 in the ASTM E1354 Cone Calorimeter and the ASTM E2058 FPA.

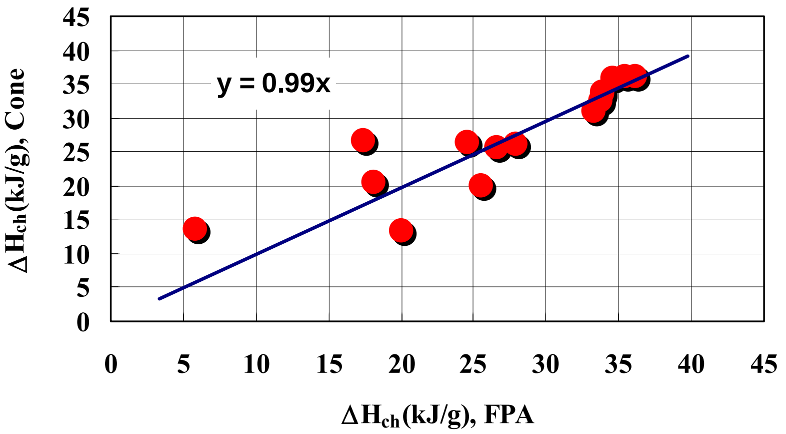


Figure 1-7. Chemical heat of combustion of vehicle plastic parts measured at 50 kW/m^2 in the ASTM E1354 Cone Calorimeter and the ASTM E2058 FPA.

The differences in the data from the ASTM E1354 Cone Calorimeter and the ASTM E2058 FPA appear to be due to differences in the surface areas during combustion, mostly due to the differences in the sample holders used in these apparatuses. The heat release rates for the charring and non-melting-type plastics agree because there is little variance in the surface areas. However, the heat release rates for the melting-type plastics are significantly different, because of the greatly increased surface areas during combustion in the FPA. The melting-type plastics drip and burn as pools; the surface areas of the pools depend on the geometry of the sample containers, which are different in the two apparatuses.

1.3.4.5 Comparisons of CO and Smoke Yields from the ASTM E1354 Cone Calorimeter and the ASTM E2058 FPA

Data for the yields of smoke and CO are shown in Fig. 1-8. Most of the yields of CO and smoke from the ASTM E1354 Cone Calorimeter are about one-half the yields from the ASTM E2058 FPA. This difference appears to be due to some type of catalytic conversion of CO and carbon to CO_2 by the hot metal in the neck of the cone through which hot products have to flow out in the Cone Calorimeter. The differences in the yield of CO due to its conversion to CO_2 are not significant in affecting the ΔH_{ch} values or the combustion efficiency.

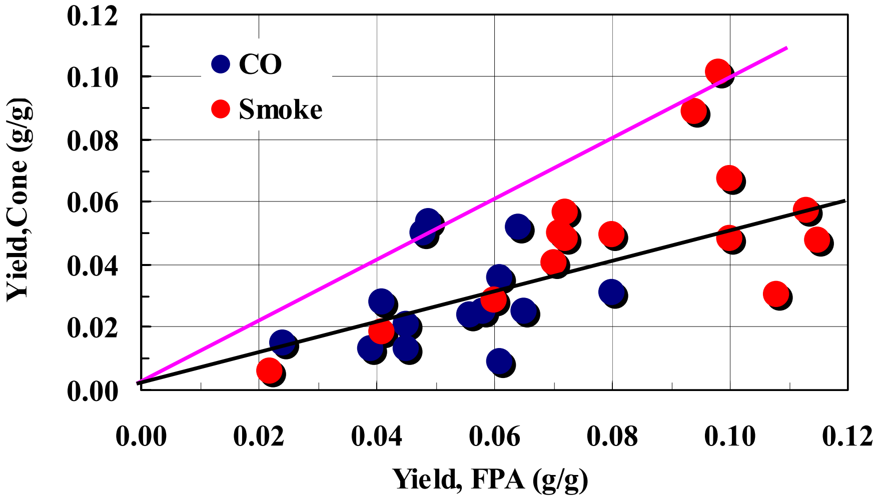


Figure 1-8. CO and smoke yields for the plastic parts of vehicles measured at 50 kW/m² in the ASTM E1354 Cone Calorimeter and the ASTM E2058 FPA.

1.3.4.6 Relationships between the Heat Release Rate and Generation Rates of Products and Thermophysical and Fire Properties of Plastics

Heat release rates and generation rates of products depend on the thermophysical and fire properties of the plastics, their shape, size and arrangement and the environment, as suggested by the following expressions [12]:

$$\dot{\mathbf{Q}}''_{\mathbf{ch}} = \dot{\mathbf{m}}''\,\Delta\mathbf{H}_{\mathbf{ch}} = (\Delta\mathbf{H}_{\mathbf{ch}} / \Delta\mathbf{H}_{\mathbf{g}})\,\dot{\mathbf{q}}''_{\mathbf{n}} \tag{4}$$

$$\dot{\mathbf{G}}''_{\mathbf{j}} = \dot{\mathbf{m}}''\,\mathbf{y}_{\mathbf{j}} = (\mathbf{y}_{\mathbf{j}} / \Delta\mathbf{H}_{\mathbf{g}})\,\dot{\mathbf{q}}''_{\mathbf{n}} \tag{5}$$

where $\dot{\mathbf{Q}}''_{\mathbf{ch}}$ is the chemical heat release rate (kW/m^2), $\dot{\mathbf{m}}''$ is the mass loss rate (g/m^2-s), $\Delta\mathbf{H}_{\mathbf{ch}}$ is chemical (effective) heat of combustion (kJ/g), $\Delta\mathbf{H}_{\mathrm{g}}$ is the heat of gasification (kJ/g), $\dot{\mathbf{q}}''_{\mathbf{n}}$ is the net heat flux to the plastic surface (kW/m^2), $\dot{\mathbf{G}}''_{\mathbf{j}}$ is the generation rate of compound j (g/m^2-s) and $\mathbf{y}_{\mathbf{j}}$ is the yield of the compound (g/g). The ratio $\Delta\mathbf{H}_{\mathrm{ch}}/\Delta\mathbf{H}_{\mathbf{g}}$ is defined as the *heat release parameter* (**HRP**), which is one of the most important fire properties of plastics governing the burning intensity of the plastic as indicated by Eq. 4 [12] (see Chapter 1, Volume II for the theory).

The gas temperature and concentration of products in the environment are direct functions of $\dot{\mathbf{Q}}''_{\mathbf{ch}}$ and $\dot{\mathbf{G}}''_{\mathbf{j}}$ as suggested by the following relationships [12]:

$$\Delta\mathbf{T}_{\mathbf{g}} = \chi_{\mathbf{con}}\mathbf{A}\,\dot{\mathbf{Q}}''_{\mathbf{ch}} / \dot{\mathbf{M}}\mathbf{c}_{\mathbf{p}} = \mathbf{A}\,\chi_{\mathbf{con}}(\Delta\mathbf{H}_{\mathbf{ch}} / \Delta\mathbf{H}_{\mathbf{g}})\,\dot{\mathbf{q}}''_{\mathbf{n}} / \dot{\mathbf{V}}_{\mathbf{a}}\rho_{\mathbf{a}}\mathbf{c}_{\mathbf{a}} \tag{6}$$

$$\mathbf{C}_{\mathbf{j}} = \mathbf{A}\dot{\mathbf{G}}''_{\mathbf{j}} / \dot{\mathbf{V}}_{\mathbf{a}} = \mathbf{A}\,(\mathbf{y}_{\mathbf{j}} / \Delta\mathbf{H}_{\mathbf{g}})\,\dot{\mathbf{q}}''_{\mathbf{n}} / \dot{\mathbf{V}}_{\mathbf{a}} \tag{7}$$

where $\Delta\mathbf{T}_{\mathbf{g}}$ is the gas temperature above ambient ($^{\mathrm{o}}$C), $\chi_{\mathbf{con}}$ is the convective component of the combustion efficiency, **A** is the surface area of the plastic burning (m^2), $\dot{\mathbf{M}}$ is the mass flow rate of the mixture of air and the fire products (g/s), $\mathbf{c}_{\mathbf{p}}$ is the heat capacity of the mixture (kJ/g-$^{\mathrm{o}}$C), $\dot{\mathbf{V}}_{\mathbf{a}}$ is the volumetric flow rate of the mixture (m^3/s), $\rho_{\mathbf{a}}$ is the density of the mixture (g/m^3), $\mathbf{C}_{\mathbf{j}}$ is the concentration of product j (g/m^3). As the fire products are diluted by air 20 to 30 times their volumes, properties of air are substituted for the properties of the mixture in Eqs. 6 and 7.

The above relationships show that the gas temperature and concentrations of products in the environment and thus the survivability of passengers in vehicle crash fires is expected to depend in part on the:

1) Thermophysical and fire properties of the plastic parts in a vehicle through $\chi_{\mathbf{con}}$, $\Delta\mathbf{H}_{\mathrm{ch}}/\Delta\mathbf{H}_{\mathbf{g}}$ (or **HRP**) and $\mathbf{y}_{\mathbf{j}}$;
2) Fire size through **A** and $\dot{\mathbf{q}}''_{\mathbf{n}}$,
3) Environmental conditions through $\dot{\mathbf{M}}$, $\dot{\mathbf{V}}_{\mathbf{a}}$, $\rho_{\mathbf{a}}$, and $\mathbf{c}_{\mathbf{p}}$.

As suggested by Eqs. 4 to 7, reducing $\Delta\mathbf{H}_{\mathbf{ch}}$, $\mathbf{y}_{\mathbf{j}}$ and $\dot{\mathbf{q}}''_{\mathbf{n}}$ values and increasing the $\Delta\mathbf{H}_{\mathbf{g}}$ values would reduce the heat release rate, generation rates of the products and gas temperature and concentrations. In many plastic parts in vehicles, large amounts of inert fillers are used, which perform dual purpose: 1) make the parts function properly and 2) fire retard the plastic parts. Figure 1-9 shows the heat release rate measured at 50 kW/m^2 in the ASTM E2058 FPA for plastic parts of the 1996 Dodge Caravan and the 1997 Chevrolet Camaro assembled from similar generic plastic, but containing different amounts of generically similar inert filler.

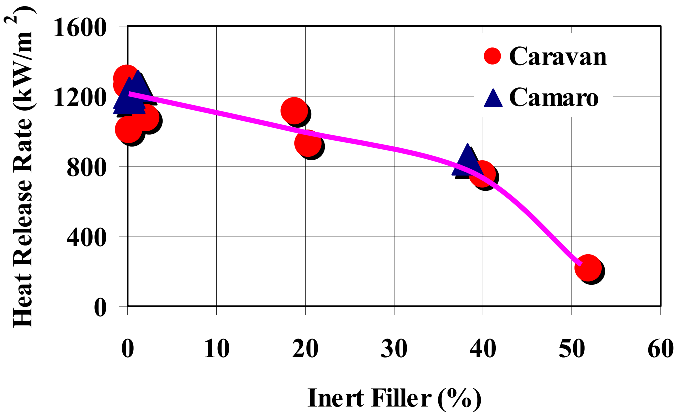


Figure 1-9. Heat release rate versus the amount of inert filler in generically similar plastic parts of vehicles measured at 50 kW/m^2 in the ASTM E2058 FPA.

As can be noted in the figure, heat release rate decreases with increase in the amount of the inert filler. There is a rapid decrease in the heat release rate above 40% of the inert filler in the plastic parts. The decrease in the heat release rate appears to be due to increase in the $\mathbf{\Delta H_g}$ values and quenching of the flame that reduces the $\mathbf{\dot{q}_n''}$ value. In addition to decreasing the heat release rate, increase in the amount of inert filler in the plastic parts, also decreases mass loss rate, release rates of products, and increases **CHF** and **TRP**, all leading to imparting higher fire resistance to the plastic parts.

The fire property data measured in the ASTM E 1354 Cone Calorimeter and the ASTM E2058 FPA are currently used world wide in various engineering codes and models to assess hazards in various types of fires. A similar approach could be taken to assess the survivability of the passengers in vehicle crash fires.

NOMENCLATURE

$\mathbf{A}$	Total exposed surface area of the plastic (m^2)
$\mathbf{a}$	Surface absorptivity
$\mathbf{c_p}$	Heat capacity (J/g-K)
$\mathbf{C_j}$	Concentration of product j (g/m^3)
$\mathbf{d}$	Physical thickness of the plastic (mm)
$\dot{\mathbf{G}}_{\mathbf{j}}''$	Generation rate of product j per unit surface area (g/m^2-s)
$\Delta\mathbf{H_{ch}}$	Chemical heat of combustion (kJ/g)
$\Delta\mathbf{H_{fusion}}$	Heat of fusion (J/g)
$\Delta\mathbf{H_g}$	Heat of gasification (kJ/g)
$\mathbf{k}$	Thermal conductivity (W/m-K);
$\dot{\mathbf{m}}''$	Mass loss rate (g/m^2-s)
$\dot{\mathbf{M}}$	Mass flow rate of the mixture of air and fire products (g/s)
$\dot{\mathbf{q}}_{\mathbf{e}}''$	External heat flux per unit surface area (kW/m^2)
$\dot{\mathbf{q}}_{\mathbf{cr}}''$	Critical heat flux per unit surface area (kW/m^2)
$\dot{\mathbf{q}}_{\mathbf{n}}''$	Net heat flux to the surface (kW/m^2)
$\dot{\mathbf{Q}}_{\mathbf{ch}}''$	Chemical heat release rate per unit surface area (kW/m^2)
$\mathbf{T_{v\ or\ d}}$	Vaporization or decomposition temperature (^oC)
$\mathbf{T_{glass}}$	Glass transition temperature (^oC)
$\mathbf{T_{ig}}$	Ignition temperature (^oC)
$\dot{\mathbf{V}}_{\mathbf{a}}$	Volumetric flow rate of the mixture of air and fire products (m^3/s)
$\mathbf{W_f}$	Total mass (g)
$\mathbf{y_j}$	Yield of product j (g/g);
Greek	
α	Thermal diffusivity (mm/s)
δ	Thermal penetration depth (mm)
$\chi_{\mathbf{con}}$	Convective component of the combustion efficiency
$\rho_{\mathbf{a}}$	Density (g/cm^3)
Subscripts	
a	ambient
ch	Chemical
d	Decomposition
f	Final
g	Gasification
ig	Ignition
j	Product
l	Molten plastic
m	Melting
n	Net
sm	Smoke
T	Total or complete
v	Vaporization

Superscripts

.	per unit of time (1/s)
“	per unit area ($1/m^2$)

General Abbreviations

CHF	Critical heat flux (kW/m^2)
FR	Fire retarded
FPI	Fire propagation index ($(m/s^{1/2})/(kW/m)^{2/3}$)
HRP	Heat Release Parameter (kJ/kJ)
TRP	Thermal response parameter ($kW\text{-}s^{1/2}/m^2$)

Plastic Abbreviations

ABS	Acrylonitrile-Butadiene-Styrene
EPDM	Ethylene-propylene-diene rubber
EVA	Ethylene-vinylacete
PC	Polycarbonate
PE	Polyethylene
PET	Polyethyleneterephthalate
PEU	Polyetherurethane
PMMA	Polymethylmethacrylate
POM	Polyoxymethylene, Polyformaldhyde, Polyacetal
PP	Polypropylene
PP-Cl	Polypropylene-chlorinated
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinylchloride
SMC	Sheet molding compound
TPO	Thermoplastic polyolefin

REFERENCES

---

1. Abu-Isa I.A., Cummings, D.R., and LaDue, D., "Thermal Properties of Automotive Plastics I. Thermal Gravimetric Analysis and Differential Scanning Calorimetry of Selected Parts from a Dodge Caravan", Technical Report R&D 8775, General Motors Research and Development Center, General Motors Corporation, Warren, MI. June, 1998.

2. Abu-Isa, I.A., "Thermal Properties of Automotive Plastics II. Thermal Conductivity of Parts Selected from a Dodge Caravan", www.nhtsa.dot.gov, Docket Number: 3588, Document Number: NHTSA-1998-3588-39, 03-30-1999.

3. Abu-Isa, I.A., and Shehdeh, J., "Thermal Properties of Automotive Plastics. III: Thermal Characteristics and Flammability of Fire Retardant Plastics", www.nhtsa.dot.gov, Docket Number: 3488, Document Number: NHTSA-1998-3588-84, June 28, 2000.

4. Abu-Isa, I.A., Shehdeh, J., and LaDue, D., "Thermal Properties of Automotive Plastics IV. Thermal Gravimetric Analysis and Differential Scanning Calorimetry of Selected Parts from a Chevrolet Camaro", www.nhtsa.dot.gov, Docket Number: 3488, Document Number: NHTSA-1998-3588-104, April 28, 2001.

5. Santrock, J., "Identification of Base Plastics in Selected Parts from a 1997 Chevrolet Camaro by Pyrolysis/Gas Chromatography/Mass Spectroscopy", www.nhtsa.dot.gov, Docket Number: 3588, Document Number: NHTSA-1998-3588-181, August 12, 2002.

6. Santrock, J., "Identification of Base Plastics in Selected Parts from a 1997 Ford Explorer by Pyrolysis/Gas Chromatography/Mass Spectroscopy and Attenuated Total Reflectance/Fourier Transform Infrared spectroscopy", www.nhtsa.dot.gov, Docket Number: 3588, Document Number: NHTSA-1998-3588-182, August 12, 2002.

7. Santrock, J., "Determination of Mole % Ethylene in Polyethylene/Ethylene Coplastic Samples by Pyrolysis/Gas Chromatography/Mass Spectroscopy Analysis", www.nhtsa.dot.gov, Docket Number: 3588, Document Number: NHTSA-1998-3588-183, August 12, 2002.

8. Battipaglia, K.C., Griffith, A.L., Huczek, J.P., Janssens, M.L., Miller, M.A., and Willson K., "Comparison of Fire Properties of Automotive Materials and Evaluation of Performance Levels", Final Report Project 01.05804, Southwest Research Institute, San Antonia, Texas, October 2003.

9. Physical Properties of Plastics Handbook, J.E. Mark (Editor), American Institute of Physics, Woodbury, New York, 1996.

10. Abu-Isa, I.A., and Shehdeh, J., "Thermal Properties of Automotive Plastics V. Flammability Test for Fire Retardant Plastics", www.nhtsa.dot.gov, Docket Number: 3588, Document Number: NHTSA-1998-3588-130, September 07, 2001.

11. Lyon, R.E., "Solid-state Thermo Chemistry of Flaming Combustion", Technical Report DOT/FAA/AR-99/56, Federal Aviation Administration, Airport and Aircraft Safety, Research and Development Division, William J. Hughes Technical Center, Atlantic City, NJ, July 1999.

12. Tewarson A., "Generation of Heat and Chemical Compounds in Fires", Section 3, Chapter 4. *The SFPE Handbook of Fire Protection Engineering*, Third Edition, pp. 3-82 to 3-161. The National Fire Protection Association Press, Quincy, MA, 2002.

13. Abu-Isa, I.A., Cummings, D.R., LaDue, D.E., and Tewarson, A., "Thermal Properties and Flammability Behavior of Automotive Plastics", www.nhtsa.dot.gov, Docket Number: 3588, Document Number: NHTSA-1998-3588-62, October 7, 1999.

14. Tewarson, A., Abu-Isa, I.A., Cummings, D.R., and LaDue, D.E., "Characterization of the Ignition Behavior of Plastics Commonly Used in the Automotive Industry", www.nhtsa.dot.gov, Docket Number: 3588, Document Number: NHTSA-1998-3588-71, December 13, 1999.

15. Abu-Isa, I.A., and Shehdeh, J., "Thermal Properties of Automotive Plastics V. Flammability Test for Fire Retardant Plastics" www.nhtsa.dot.gov, Docket Number: 3588, Document Number: NHTSA-1998-3588-130, September 07, 2001.

16. Tewarson, A., "A Study of the Flammability of Plastics in Vehicle Parts", www.nhtsa.dot.gov, Docket Number: 3588, Document Number: NHTSA-1998-3588-1, July 22, 1998.

17. Tewarson, A., "Fire Behavior of Automotive Plastics", 8th International Fire and Material Conference, San Francisco, CA, Interscience Communications, UK, 2003.

18. Ohlemiller, T.J., and Shields, J.R., "The Effect of Plastic Resin Substitution on the Flammability of a Standardized Automotive Component in Laboratory Tests", www.nhtsa.dot.gov, Docket Number: 3588, Document Number: NHTSA-1998-3588-184, October 21, 2002.

19. ASTM Standard Test Methods. The American Society for Testing and Materials, Annual Books of ASTM Standards.

20. Federal Motor Vehicle Safety Standard (FMVSS), Part 571.301: Fuel System Integrity; Part 571.302: Flammability of Interior Materials, Code of Federal Regulations (CFR), Volume 49, Chapter V, October 1, 2003.

21. Drysdale, D., An Introduction to Fire Dynamics, John Wiley and Sons, New York, NY, 1985.

22. Quintiere, J.G., Principles of Fire Behavior, Delmar Publishers, New York, NY, 1998.

23. Quintiere, J.G., "Surface Flame Spread", Section 2, Chapter 12. *The SFPE Handbook of Fire Protection Engineering*, Third Edition, pp. 2-246 to 2-257. The National Fire Protection Association Press, Quincy, MA, 2002.

24. Fernandez-Pello, A.C., and Hirano, T., "Controlling Mechanisms of Flame Spread", *Combustion Science & Technology*, **32**, 1-31, 1983.

25. Santrock, J., "Full Scale Vehicle Fire Tests of a Control Vehicle and a Test Vehicle Containing an HVAC Module made from Plastics Containing Flame Retardant Chemicals", Part 1, www.nhtsa.dot.gov, Docket Number: 3588, Document Number: NHTSA-1998-3588-190, October 22, 2002.

26. Tewarson, A., Khan, M. M., Wu, P. K. S., and Bill, R. G., "Flammability of Clean Room Plastic Materials for the Semiconductor Industry" *J. Fire and Materials*, **25**, 31-42, 2001.

27. Purser, D.A., "Toxicity Assessment of Combustion Products", Section 2, Chapter 6. *The SFPE Handbook of Fire Protection Engineering*, Third Edition, pp. 2-83 to 2-171. The National Fire Protection Association Press, Quincy, MA, 2002.

CHAPTER II

THERMOPHYSICAL AND FIRE PROPERTIES OF ENGINE COMPARTMENT FLUIDS

2.1 INTRODUCTION

The Fatal Analysis Reporting System (FARS), the National Automotive Sampling System (NASS) and the Crashworthiness Data System (CDS) databases used in the planning of the GM sponsored studies, under the DOT/GM Settlement Agreement (Chapter 1, Volume I), identified that in many vehicle crashes, fires were started by the engine compartment fluids. The engine compartment fires also contributed towards the burning intensity of the fires (Volume I, Table A-1, Appendix A). Fires were started as the released vapors and/or liquid droplet sprays of the engine compartment fluids encountered hot surfaces and sparks in vehicle crashes. It should be noted that these types of fires are common in industrial accidents associated with the release of fluids and many studies have been performed on hazards presented by these types of fires and property protection needs [1,2,3,4,5,6 and references therein]. Standards and specifications have been developed for the fire hazard classifications of the fluids [1,2,4]. Some of these standards and specifications have also been used for the fire hazard classification of the engine compartment fluids, such as the fire safety specifications listed by the National Fire Protection Association (NFPA) and the U.S. Department of Transportation (DOT) for storage and transport of the fluids [1]. In these specifications, fluids are classified for their fire hazards based on their flash points ($\mathbf{T_{flash}}$) and boiling points ($\mathbf{T_b}$), as listed in Table 2-1 [1].

In these specifications, $\mathbf{T_b}$ is defined in a variety of ways. For example, the NFPA specification defines $\mathbf{T_b}$ as the temperature for the initial 20% evaporation of the fluid [1]. DOT specification defines $\mathbf{T_b}$ as the initial boiling point ($\mathbf{T_{ib}}$) of the fluid [1]. The $\mathbf{T_{ib}}$ and $\mathbf{T_b}$ have also been defined in the ASTM D2887-97[1] [7].

---

[1] ASTM D2887-97 defines $\mathbf{T_b}$ as having two values, based on the total integrated response of the detector of a gas chromatograph (GC). Temperature corresponding to 0.5 % integrated response of the GC detector is defined as the initial boiling point ($\mathbf{T_{ib}}$). Temperature corresponding to 99.5 % integrated response of the GC detector is defined as the final boiling point ($\mathbf{T_{fb}}$).

Table 2-1. NFPA/DOT Specifications for Fire Hazard Classification of Fluids [1]

NFPA			DOT	
Fluid Classification	**Hazard Rating**	**Criteria (^{o}C)**	**Packing Group**	**Criteria (^{o}C)**
IA	4	$\mathbf{T_b} < 37.8$; $\mathbf{T_{flash}} < 22.8$	I	$\mathbf{T_b} \leq 35$
IB	3	$\mathbf{T_b} \geq 37.8$; $\mathbf{T_{flash}} < 22.8$	II	$\mathbf{T_b} > 35$; $\mathbf{T_{flash}} < 23$
IC	3	$22.8 \leq \mathbf{T_{flash}} < 37.8$	III	$\mathbf{T_b} > 35$; $60.5 \geq \mathbf{T_{flash}} \geq 23$
II	2	$37.8 \leq \mathbf{T_{flash}} < 60$		
III A	2	$60 \leq \mathbf{T_{flash}} < 93.4$		
IIIB	1	$\mathbf{T_{flash}} \geq 93.4$		
0	0	$\mathbf{T_b} > 815.5$ for 5 minutes		

The engine compartment fluids are complex mixtures of hydrocarbon-based fluids (in majority), glycol-based fluids (antifreeze with water and brake fluids), and alcohol-based fluids with water (windshield washing fluids). Because of the complex compositions of the engine compartment fluids, $\mathbf{T_b}$ cannot be defined in a simple fashion [8]. Furthermore, it is not apparent how $\mathbf{T_{flash}}$, $\mathbf{T_{ib}}$, **and** $\mathbf{T_b}$ values alone could be used for the fluid hazard classifications and for the assessment of the passenger survivability in vehicle crash fires. These values in combination with other thermophysical and fire properties could be used following the practices of various industries such as the chemical, mining and fuel industries [1,2,3,4,5,6]. In these industries, $\mathbf{T_{flash}}$, $\mathbf{T_{ib}}$, **and** $\mathbf{T_b}$ values along with other thermophysical and fire properties of fluids are used in the engineering models to assess industrial fire hazards associated with the accidental release of fluids and their burning as jets and as pool fires [1,2,3,4,5,6].

This approach was undertaken in the planning of the GM sponsored studies [8,9,10,11]. Several engine compartment fluids were selected, their thermophysical and fire properties were quantified, and the possibility of their use in the fire hazard classification of the fluids pertinent to vehicle crash fires was explored [8,9,10,11]. The following properties were quantified:

- Density (ρ);
- $\mathbf{T_b}$[2] and distillation temperature and fraction;

---

[2] Boiling point for a single component fluid is generally defined as the temperature at which the vapor pressure equals one standard atmosphere [1].

- Heat capacity (**c_p**); **T_{flash}**[3], fire point (**T_{fire}**)[4], hot surface ignition (**T_{hot}**) and autoignition temperature (**AIT** or **T_a**)[5];
- Upper and lower flammability limits (**UFL** and **LFL**);
- Heat of vaporization **(ΔH_v**), heat of combustion, **ΔH_i** and yields of products, **y_j**;

The properties of the engine compartment fluids were quantified following the ASTM Standard Test Methods for Fluids [7] and the ASTM E2058 FPA for solids with procedure modified for the fluids [7]. A special test method was developed by GM for the hot surface ignition of the engine compartment fluids [9]. These methods are discussed briefly in Appendix B-1.

In the GM sponsored studies, attempts were made to correlate the properties of the engine compartment fluids for their resistance to ignition, combustion and flame spread, utilizing relationships from the literature [1,2,3,4,5,6,12,13,14,15,16,17,18,19,20]. These relationships are enumerated in Appendix B-2 along with the listing of the literature data for the thermophysical and fire properties of fluids other than the engine compartment fluids.

2.2 ENGINE COMPARTMENT FLUIDS

The engine compartment fluids examined in the tests are listed in Table B-3-1 and B-3-2 in Appendix B-3. The engine compartment fluids are used for the lubrication of the engine (to separate moving surfaces to minimize friction and wear), power steering, automatic transmission, braking, prevention of freezing of water, and for washing the windshield [21,22]. A brief summary of the compositions of the fluids used in the tests is listed in Table 2-2.

As can be noted, the hydrocarbon-based fluids (motor oils, synthetic motor oils, power steering fluids, transmission fluids, and gear lubrication fluids) are complex mixtures of hydrocarbon fluids. The non-hydrocarbon-based fluids (brake fluids, antifreeze, engine coolants, and windshield washing fluids) either are single components fluids or are mixed with water.

Due to the complexities of the hydrocarbon-based fluids, interpretation of the measured thermo-physical and fire property data are difficult, compared to those for the simpler non-

---

[3] Flash point is the minimum temperature at which a fluid gives off sufficient vapors to form an ignitable mixture with air near the surface of the fluid or within the test vessel used. Flash points are reported as open or closed cup flash points [2,3].

[4] Fire point is the lowest temperature at which a fluid in an open container will give off enough vapors to continue to burn once ignited. It is generally slightly above the open-cup flash point [2,3].

[5] Autoignition temperature is a rapid, self-sustaining, sometimes audible gas-phase reaction of the sample or its decomposition products with an oxidant. A readily visible yellow or blue flame usually accompanies the reaction [2,3].

hydrocarbon based fluids. In order to explain variations in the data and their validity, non-hydrocarbon-based fluid data are generally used as references. The thermophysical and fire properties, test methods, and laboratories where measurements were made are listed in Table 2-3.

Table 2-2. Compositions of Engine Compartment Fluids Examined in the Tests [8]

Fluid	Major Components
Motor oils	Petroleum distillates (range about C_{15} to C_{35}). Varying amounts of light hydrocarbons from gasoline in used motor oils (range about C_5 to C_{15}).
Synthetic motor oils	Bimodal mixture of hydrocarbons (range of C_{25} to C_{37}, peaks at about C_{27} and C_{35} or hydrocarbon mixtures, range of about C_{17} to C_{37} or the range of about C_{19} to > C_{38}) Varying amounts of light hydrocarbons from gasoline in used motor oils (range about C_5 to C_{15}).
Power Steering fluids	Petroleum distillates (range of about C_{15} to C_{35} in the new fluids; about C_{17} to C_{36} in the used fluids).
Transmission fluids	Petroleum distillates (range about C_{15} to C_{35})
Gear Lubrication fluids	Petroleum distillates (range about C_{23} to > C_{38})
Break fluids	Mixtures of methyl-, ethyl, or butyl-terminated ethylene glycol oligomers (dimmer through hexamer)
Windshield washers	Water and methanol
Antifreeze/coolant	Diluted with 1:1 with water. Ethylene glycol or diethyl glycol or propylene glycol.

Table 2-3. Fluid Properties Measured, Test Methods, and Laboratories [11]

Property	Test Method	Laboratory
Test Methods for the Measurements of Thermo-Physical Properties		
Density	ASTM D287 (API Gravity)	UEC[a]
Boiling Point	ASTM D 1120	UEC[a]
Boiling Range Distribution of Petroleum Fractions	ASTM D86 and D2887	UEC[a] and GM
Flash Point	ASTM D93	FM Global
Autoignition Temperature	ASTM E659	UEC[a]
Hot Metal Surface Ignition	Non-standard (developed by GM)	GM
Lower and Upper Limits of Flammability	ASTM E681	Chilworth[b]
Heat Capacity	ASTM D2890 and E 1269	GM
Test Methods for the Measurements of Fire Properties		
Heat of Vaporization	MDSC	GM
Heat of Complete Combustion	ASTM D240	FM Global
Heat and Product Release Rates	Modified ASTM E2058	FM Global
Heat of combustion/yields of products		

a: UEC Fuels and Lubrication Laboratories, Monroeville, PA; **b**: Chilworth Technology, Monmouth Junction, NJ.

2.3 DATA FOR THE THERMOPHYSICAL AND FIRE PROPERTIES OF THE ENGINE COMPARTMENT FLUIDS

The quantified data for the thermophysical and fire properties of the engine compartment fluids are listed in Tables B-3-3 to B-3-18 in Appendix B-3.

2.3.1 Density of the Engine Compartment Fluids

Densities of the engine compartment fluids measured following the ASTM D287 Standard Test Method (Appendix B-1) and by the direct measurement of the mass and volume of the fluids are listed in Table B-3-3 in Appendix B-3. These data show that the densities of the hydrocarbon-based fluids (motor oils, gear lubrication fluid, power steering fluids, and automatic transmission fluid) are less than unity. The densities of the non-hydrocarbon-based fluids (brake fluids, antifreeze, engine coolants and windshield washing fluids) are greater than unity. There is little difference between the densities of the new and used fluids.

2.3.2 Boiling Point and Distillation Data for the Engine Compartment Fluids

The distillation temperature ranges and boiling points ($\mathbf{T_b}$) were measured following the ASTM D1120, ASTM D86, and ASTM 2887 Standard Test Methods (Appendix B-1). The measured data for the boiling point ($\mathbf{T_b}$), initial boiling point ($\mathbf{T_{ib}}$), final boiling point ($\mathbf{T_{fb}}$) and percent distillation and temperature are listed in Tables B-3-4 to B-3-7 in Appendix B-3.

2.3.2.1 Boiling Points of Fluids Measured by the ASTM D1120 Standard Test Method

The $\mathbf{T_b}$ values for the hydrocarbon-based fluids (motor oils, gear lubrication fluid, power steering fluids and automatic transmission fluids) were greater than 300 ^{o}C and thus could not be measured as they were beyond the range of the Apparatus at UEC. The $\mathbf{T_b}$ values for the non-hydrocarbon based fluids were less 300 ^{o}C and thus it was possible to measure them by this Test Method. The averages of these measured $\mathbf{T_b}$ values for the brake fluids, antifreeze, engine coolants, and windshield washing fluids are listed in Table 2-4. Following is a summary of the average $\mathbf{T_b}$ values for the non-hydrocarbon based fluids:

- Brake fluids (polyglycol ethers): $\mathbf{T_b}$ = 261 ^{o}C;
- Antifreeze (ethylene or propylene glycol): $\mathbf{T_b}$ = 164 ^{o}C (literature value is 198 ^{o}C for ethylene glycol);
- Engine coolants (50:50 mixtures of ethylene or propylene glycol and water): $\mathbf{T_b}$ = 107 ^{o}C, which is closer to the boiling point of water ($\mathbf{T_b}$ = 100 ^{o}C).
- Windshield washing fluids (methanol-water mixtures): $\mathbf{T_b}$ = 81 ^{o}C, which is between the $\mathbf{T_b}$ values for methanol (65 ^{o}C) and water (100 ^{o}C).

2.3.2.2 Initial and Final Boiling Points of Fluids Measured by the ASTM D86 Standard Test Method

The ASTM D86 Test Method, designed for the distillation of petroleum products, is similar to the ASTM D1120 Test Method, except that the condensate is separated from the boiling fluid via a condenser.

The $\mathbf{T_{ib}}$ to $\mathbf{T_{fb}}$ value ranges for the hydrocarbon-based fluids (motor oils, gear lubrication fluid, power steering fluids, and automatic transmission fluids) could not be measured by this Test Method either, as they were beyond the range of the Apparatus at UEC. The $\mathbf{T_{ib}}$ to$\mathbf{T_{fb}}$ value ranges for the non-hydrocarbon based fluids, however, were measured by UEC as they were within the range of the Apparatus. The measured $\mathbf{T_{ib}}$, $\mathbf{T_{fb}}$, and the distillation temperature ranges for the non-hydrocarbon based fluids are listed in Table B-3-4 in Appendix B-3. The average values for the distillation temperature ranges ($\mathbf{T_{ib}}$ to $\mathbf{T_{fb}}$) for similar groups of fluids are listed in Table 2-4. Data in Table 2-4 show that the average $\mathbf{T_{ib}}$ values from the ASTM D86 Method are slightly lower than the $\mathbf{T_{b}}$ values from the ASTM D1120 Method for the non-hydrocarbon based engine compartment fluids.

2.3.2.3 Initial and Final Boiling Points of Fluids Measured by the ASTM D2887 Standard Test Method

This Standard Test Method is based on the gas chromatographic measurements and is capable of measuring the $\mathbf{T_{ib}}$, $\mathbf{T_{fb}}$ and the distillation temperature ranges for all the fluids. Both GM and UEC used this Method; their measured data are listed in Table B-3-5 to B-3-7 in Appendix B-3.

Table 2-4. Average Data for Ignition, Distillation and Vaporization for the Engine Compartment Fluids [8,11]

Fluids	New/ Used	Average (^{o}C)			Lab	Average (^{o}C)			MDSC
		T_{flash}	T_a	T_{hot}		T_b	Distillation Range (T_{ib} to T_{fb})		Vaporization Range (^{o}C)
		D93	E659	GM		D1120	D2887	D86	
Motor Oils Petroleum)	New	187	351	310	GM		318-499		170-315
					UEC	> 304	293-560		
	Used	134	>382	313	GM		158-506		311-369
					UEC		155-515		
Motor Oils (synthetic)	New	188	360	323	GM		309-516		199-330
					UEC	> 304	265-558		
	Used	160	>382	324	GM		133-514		324-375
					UEC		148-577		
Gear Lubrication Fluid	New	154	>382	325	GM		54-524		201-290
					UEC	> 304	124-622		
Power Steering Fluids	New	188	>382	312	GM		334-515		159-300
					UEC	> 304	303-543		
	Used	203	338	321	GM		239-523		378-431
					UEC		256-554		
Automatic Transmission Fluids	New	177	333	314	GM		241-516		217-306
					UEC	> 304	261-503		
	Used	163	>382	304	GM		279-500		266-330
					UEC		269-531		
Brake Fluids	New	140	329	287	UEC	261		246-330	209-297
	Used	123	283	303					134-239
Antifreeze	New	116	>382	506	GM		$T_b = 197$		144-221
					UEC	164		147-196	
Engine Coolants	New	NI	>382	518	GM		$T_b = 192$		211-250
					UEC	107		101-191	
	Used	110	343	528	GM		$T_b = 197$		180-238
					UEC			101-206	
Windshield Washing Fluids	New	32	>382		GM		$T_b = 65$		187-220
					UEC	81		74-142	

The average values of $\mathbf{T_{ib}}$ and $\mathbf{T_{fb}}$ for similar groups of fluids from the measurements made by GM (Table B-3-7) are listed in Table 2-4 and plotted in Fig. 2-1 along with the $\mathbf{T_{ib}}$ and $\mathbf{T_{fb}}$ values from the UEC measurements.

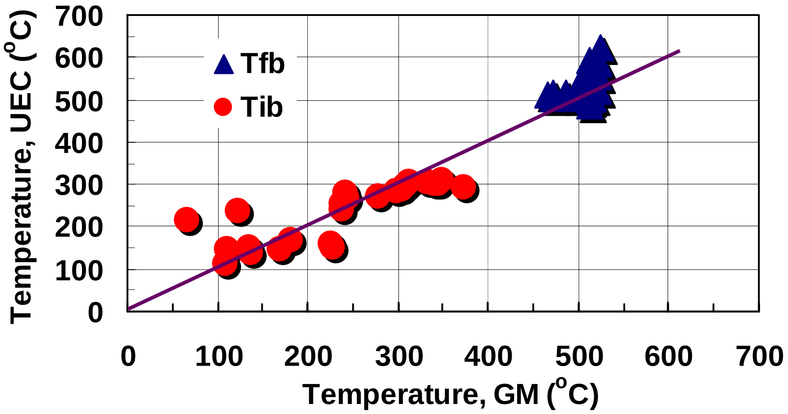


Figure 2-1 Initial and final boiling points of selected engine compartment fluids measured by GM [9] and UEC [11] by the ASTM D2887 Standard Test Method.

Figure 2-1 shows that there is a good agreement between the $\mathbf{T_{ib}}$ and $\mathbf{T_{fb}}$ values measured by GM and UEC, with a few exceptions.

The distillation data show that the D2887 Standard Test Method is capable of providing data over a wide temperature range, unlike ASTM D1120 and ASTM D86 Standard Test Methods. The data measured by this Method also appear to be reasonably accurate. For example, for methanol $\mathbf{T_b}$ = 65 °C from the ASTM D2887 Test Method (literature value = 65 °C); for ethylene glycol in antifreeze and engine coolant, $\mathbf{T_b}$ = 197 °C and 192 °C (new)/197 °C (used) respectively from the ASTM D2887 Test Method compared to the literature value of 198 °C.

2.3.3 Vaporization

The vaporization behaviors of the selected engine compartment fluids were examined by the Modulated Differential Scanning Calorimetry (MDSC) (Appendix B-1) [10]. The fluids were heated in a hermetically sealed aluminum pans with a pinhole covered by a steel ball to avoid boil over of the fluids before reaching the boiling point. Data were measured by GM for the vaporization temperature range, peak vaporization temperature ($\mathbf{T_{v,peak}}$) and the vaporization energy ($\mathbf{E_v}$). These data are listed in Table B-3-8 in Appendix B-3. The average values of the vaporization temperature range for similar groups of fluids are listed in Table 2-4.

The average data in Table 2-4 show that the range for the vaporization temperature for new fluids from the MDSC are lower than the distillation temperature range from the ASTM D 2887 Test Method for the hydrocarbon-based fluids. However, the trend is reversed for the used fluids. For the non-hydrocarbon based fluids, there are closer agreements between the $\mathbf{T_b}$ values and the distillation and vaporization temperature ranges from the ASTM D1120, D2887, D86 Test Methods, and the MDSC, except for the fluids diluted with water (engine coolant and windshield washing fluids).

2.3.4 Ignition

The ignition behavior of a fluid is expressed in terms of its flash point ($\mathbf{T_{flash}}$), its fire point ($\mathbf{T_{fire}}$), its autoignition temperature ($\mathbf{T_a}$) and its hot surface ignition temperature ($\mathbf{T_{hot}}$) (Appendix B-2). In the GM sponsored studies, measurements were made for $\mathbf{T_{flash}}$ and $\mathbf{T_a}$ for the engine compartment fluids following ASTM Standard Test Methods [7]. The values of $\mathbf{T_{hot}}$ values were measured by a test method developed by GM [9]. These test methods are briefly described in Appendix B-1.

2.3.4.1 Flash Point

The value of $\mathbf{T_{flash}}$ of a fluid is the minimum temperature at which the fluid gives off sufficient vapors to form an ignitable mixture with air near the surface of the fluid or within the test vessel used [2,3]. $\mathbf{T_{flash}}$ values for the fluids were measured by FM Global following the ASTM D93 Standard Test Method. The measured values are listed in Table B-3-9 in Appendix B-3 and the average $\mathbf{T_{flash}}$ values for similar groups of fluids are listed in Table 2-4. Both $\mathbf{T_{flash}}$ and $\mathbf{T_{ib}}$ values of fluids are governed by the initial fluid volatility and thus are interrelated as shown in Fig. 2-2. A regression analysis of the data suggests that $\mathbf{T_{flash} \approx 0.63\ T_{ib}}$. The lowest values for $\mathbf{T_{ib}}$ and $\mathbf{T_{flash}}$ are 73 ^{o}C and 30 ^{o}C respectively for the new windshield washing (B10FF020) for winter, which is a mixture of methanol and water. These low

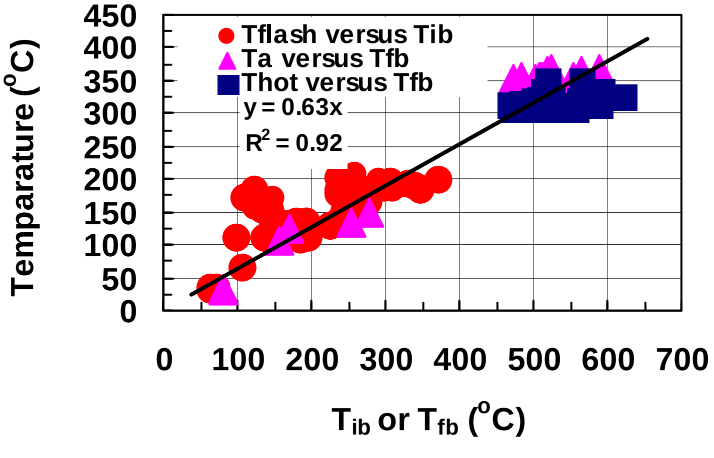


Figure 2-2. Relationship between the flash point and initial boiling point and between the autoignition temperature, hot surface ignition temperature, and final boiling point for engine compartment fluids.

values are due to preferential vaporization of methanol relative to water and suggest that this fluid could easily initiate a fire in the engine compartment of a vehicle in a crash.

The NFPA and DOT specifications use $\mathbf{T_{flash}}$ and $\mathbf{T_b}$ values of fluids for their fire hazard classifications [1]. NFPA uses the temperature for 20% distillation as the $\mathbf{T_b}$ values, whereas DOT uses the $\mathbf{T_{ib}}$ values (Table 2-1). According to these criteria, the fire hazards of selected engine compartment fluids would be significantly lower than the fluids classified as IIIB or 0 according to NFPA or Packing Group III according to DOT**.**

Currently, $\mathbf{T_{flash}}$ and $\mathbf{T_b}$ are defined in a variety of ways by worldwide organizations. There is thus a need to agree upon standard definitions that allow classification of liquid mixtures based on $\mathbf{T_b}$ or its combination with $\mathbf{T_{flash}}$ [1]. Based on the standard specifications of varieties of worldwide organizations, the United Nations Conference on Environment and Development (UNCED) criteria have been developed, where fluids are classified into six distinct levels of fire hazards [1], as listed in Table 2-5. A comparison of the average data from Table 2-4 with fire hazard criteria in Table 2-5 suggest that engine compartment fluids are below the low UNCED hazard level, except for the windshield washing fluid, which would be in the medium hazard level.

Table 2-5. United Nations Conference on Environment and Development (UNCED) "Harmonization" Criteria for the Fire Hazard Classification of Fluids

Hazard Level	Criteria (^oC)
Very high danger	$\mathbf{T_{ib}} \leq 35$ and $\mathbf{T_{flash}} < 23$
High danger	$\mathbf{T_{ib}} > 35$ and $\mathbf{T_{flash}} < 23$
Medium danger	$23 \leq \mathbf{T_{flash}} \leq 60$
Low danger	$60 < \mathbf{T_{flash}} < 93$

2.3.4.2 Autoignition Temperature

Autoignition temperature is a rapid, self-sustaining, sometimes audible gas-phase reaction of the sample or its decomposition products with an oxidant. A readily visible yellow or blue flame usually accompanies the reaction [2,3]. As the temperature of a fluid is increased, the fluid is first heated to its flash point ($\mathbf{T_{flash}}$). With further increase in the temperature, the fluid is heated to its fire point ($\mathbf{T_{fire}}$). If the heating of the fluid is continued, the autoignition temperature ($\mathbf{T_a}$) is reached, where its vapors mix with air and ignite without a pilot flame or a heat source.

The **T_a** values for the selected engine compartment fluids were measured by UEC following the ASTM E659 Standard Test Method (Appendix B-1). The measured **T_a** values are listed in Table B-3-9 in Appendix B-3. The averages of these values for each group of fluids are listed in Table 2-4 and plotted in Fig. 2-2 versus the final boiling points (**T_{fb}**) of the fluids.

In Fig. 2-2, it can be noted that **$T_a \approx 0.63\ T_{fb}$**, which is very similar to the relationship between **T_{flash}** and **T_{ib}**, as expected because autoignition temperature is also governed by the fluid volatility, although in the later stages of fluid distillation. Since the relationship between **T_a** and **T_{fb}** and between **T_{flash}** and **T_{ib}** are similar, the following relationship is suggested:

$$\mathbf{T_{flash} / T_a \approx T_{ib} / T_{fb}} \qquad (1)$$

This relationship is supported by the data for the engine compartment fluids plotted in Fig. 2-3.

2.3.4.3 Hot Surface Ignition

The hot surface ignition behaviors of the selected engine compartment fluids were examined by a new test method developed by GM, where a crucible and a hemisphere cast from gray iron using green sand molds were used (Appendix B-1). In each test, the crucible was heated electrically, whereas the hemisphere was heated by a gas burner. Measured volume of the fluid was quickly poured into the hot crucible or on top of the hot hemisphere. The time and temperature of the crucible and the hemisphere were recorded for the ignition of the fluid. Five or more replicate tests were performed at each crucible or hemisphere temperature. Data measured in this fashion are listed in Tables B-3-10 to B-3-14 in Appendix B-3.

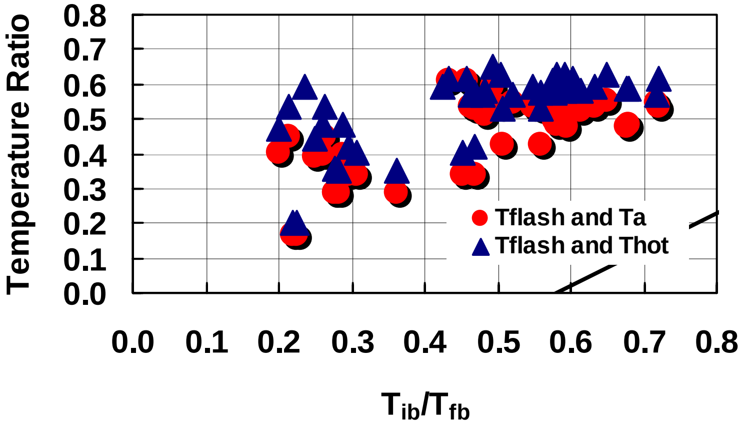


FIGURE 2-3 Ratio of the flash point to autoignition temperature and flash point to hot surface temperature versus the ratio of the initial and final boiling points for the engine compartment fluids.

The **T_{hot}** values from the crucible, in Tables B-3-10 to B-3-13 in Appendix B-3, are measured in enclosed spaces, whereas the **T_{hot}** values from hot cast iron hemisphere, in Tables B-

3-14 in Appendix B-3, are measured in the open. The $\mathbf{T_{hot}}$ values from the hemisphere increase significantly with increase in the airflow velocity near the surface and for airflow rate of 2.24 m/s, there is no ignition of the fluid (Table A-3-14, #B10FF015). The $\mathbf{T_{hot}}$ values from crucible are affected slightly by the fluid temperature (Table B-3-12, #B10FF015). The $\mathbf{T_{hot}}$ values from the hemisphere (minimum temperature for 5/5 ignitions) at zero airflow velocity are about 60 ^{o}C higher than the $\mathbf{T_{hot}}$ values from the crucible.

The average $\mathbf{T_{hot}}$ values for each class of fluids are listed in Table 2-4 and plotted in Fig. 2-2 against $\mathbf{T_{fb}}$. The data in Fig. 2-2 show that $\mathbf{T_{hot} \approx 0.54\ T_{fb}}$, and since $\mathbf{T_a \approx 0.63\ T_{fb}}$, it can be shown that $\mathbf{T_{hot}} \approx 0.86\ \mathbf{T_a}$. This is supported by the average experimental data listed in Table 2-4. From Eq. 1 and $\mathbf{T_{hot}} \approx 0.86\ \mathbf{T_a}$, the following expressions can be derived:

$$\mathbf{T_{flash} / T_a \approx T_{ib} / T_{fb}} \tag{2}$$

$$\mathbf{T_{flash} / T_{hot} \approx 1.20\, T_{ib} / T_{fb}} \tag{3}$$

Average data from Table 2-4 plotted in Fig. 2-3 support this relationship, although there is scatter in the data for $\mathbf{T_{flash}/T_{hot}}$ versus $\mathbf{T_{ib}/T_{fb}}$ values.

2.3.4.4 Heat Capacity of the Engine Compartment Fluids and Their Vapors

The data for the heat capacity of fluids were determined from the average mean boiling points and the API gravity values following the ASTM D2890 Standard Test Method [7,8]. The heat capacity values for the vapors of the engine compartment fluids were determined by using MDSC following the ASTM E1269 Standard Test Method [10]. The test methods are described briefly in Appendix A-1. The measured data are listed in Table B-3-15 and B-3-16 in Appendix B-3. Literature data for the heat capacities of gases and liquids are listed in Tables B-2-3, B-2-5, B-2-7, and B-2-9 in Appendix B-2.

The heat capacity data for the engine compartment fluids and their vapors plotted in Fig. 2-4, show that the values for liquids increase linearly with temperature, whereas for the

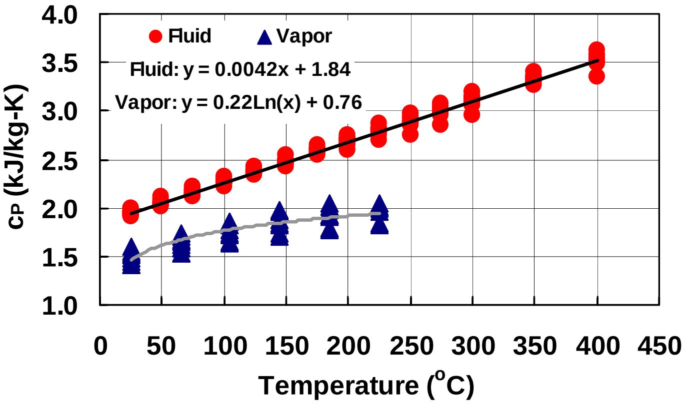


Figure 2-4 Heat capacities of selected hydrocarbon-based engine compartment fluids and their vapors.

vapors, the values increase non-linearly with temperature. The data in Fig. 2-4 suggest that the heat capacity values for fluids are higher than the values for their vapors. A similar trend is indicated by the literature data for the hydrocarbon fluids [23]. For these fluids, the ratios of the heat capacity values for the vapors to liquids are in the range of 0.69 to 0.75 and decrease to 0.56 for the oxygenated fluids. The average ratio of the heat capacity of vapors to that for the liquids for the selected hydrocarbon–based engine compartment fluids is 0.76 (standard deviation is 0.05).

2.3.4.5 Lower and Upper Flammability Limits

The lower and upper flammability limits (**LFL** and **UFL** respectively) of the selected engine compartment fluids were measured by UEC following the ASTM E681 Standard Test Method [11]. The measured values for the engine compartment fluids are listed in Table B-3-17 in Appendix B-3. The **LFL** and **UFL** values for other fluids reported in the literature are included in Tables B-2-3, B-2-5, B-2-7, B-2-9, and B-2-11 in Appendix B-2.

The **LFL** and **UFL** values for the engine compartment fluids are similar to the values for other fluids reported in the literature. Aging of the engine compartment fluids does not appear to affect the flammability limits. In general, the **LFL** and **UFL** values correlate, except at low **UFL** values, as shown in Fig. 2-5. A general correlation between the **LFL** and **UFL** values is included in the figure.

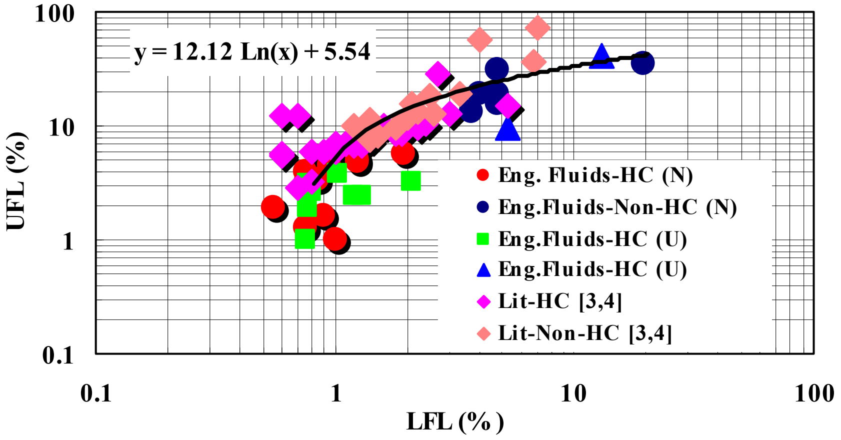


Figure 2-5 Correlation between the **LFL** and **UFL** values of the engine compartment fluids and other fluids. HC: hydrocarbon based fluids; Non-HC: non-hydrocarbon based fluids; Eng.Fluids: engine compartment fluids; Lit: literature data for other fluids: N: new; U: used.

The **LFL** and **UFL** values are higher for the non-hydrocarbon-based fluids. Addition of water increases the limits. For example, **LFL** = 5.0 to 5.5 for B10FF021 and 3.8 to 4.3 for

B10FF022, whereas **LFL** = 12.1 for B10FF035 (B10FF021 + 50% water) and 7.5 for B10FF036 (B10FF022 + 50% water. Similarly, **UFL** = 30.1 to 31.1 for B10FF021 and 18.4 to 19.4 for B10FF022, whereas UFL = 42.0 for B10FF035 (B10FF021 + 50% water) and 37.1 to 37.7 for B10FF036 (B10FF022 + 50% water).

2.3.4.6 Heat of Vaporization

The vaporization behavior of the engine compartment fluids was examined by the Modulated Differential Scanning Calorimetry (MDC) by GM [10]. The measured vaporization data were used to determine the vaporization temperature range, peak vaporization temperature ($\mathbf{T_{v,peak}}$) and the vaporization energy ($\mathbf{E_v}$). These data are listed in Table B-3-8 in Appendix B-3.

The measured vaporization data in Table B-3-8 were used to calculate the heat of vaporization ($\mathbf{\Delta H_v}$) of the fluids, using Eq. B-2-17 (Appendix B-2) with $\mathbf{T_o}$ = 25 ^{o}C and $\mathbf{T_b}$ = initial vaporization temperature. The values of $\mathbf{\Delta H_v}$ calculated in this fashion for the engine compartment fluids are listed in Table B-3-16 in Appendix B-3. The average values of $\mathbf{\Delta H_v}$ for similar class of the engine compartment fluids are listed in Table 2-6. These values for the engine compartment fluids are similar to the $\mathbf{\Delta H_v}$ values for generically similar fluids reported in the literature (Tables B-2-4, B-2-6, B-2-8, B-2-10, B-2-12, and B-2-13 in Appendix B-2). The $\mathbf{\Delta H_v}$ values for the engine compartment fluids provide the necessary information to calculate:

- Molecular weights (**M)** of the engine compartment fluids in combination with their boiling points, $\mathbf{T_b}$ (Eq.B-2-5 in Appendix B-2);
- Release rate of the engine compartment fluid vapors ($\dot{\mathbf{m}}_\mathbf{f}''$) in combination with the net heat flux, $\dot{\mathbf{q}}_\mathbf{n}''$ (Eq. B-2-11 in Appendix B-2; for large pool fires of fluids, $\dot{\mathbf{q}}_\mathbf{n}'' \approx$ 33 kW/m^2, irrespective of the generic nature of the fluids);
- Heat release rate ($\dot{\mathbf{Q}}_\mathbf{i}''$) in the burning of the engine compartment fluids in combination with the $\dot{\mathbf{m}}_\mathbf{f}''$ value and heat of combustion, $\mathbf{\Delta H_i}$ (Eqs. B-2-12 and B-2-13 in Appendix B-2);
- Generation rates of products ($\dot{\mathbf{G}}_\mathbf{j}''$) in the burning of the engine compartment fluids in combination with the $\dot{\mathbf{m}}_\mathbf{f}''$ value and product yields, $\mathbf{y_j}$ (Eqs. B-2-14 and B-2-15 in Appendix B-2);
- Lower flammability limit (**LFL**) for the engine compartment fluids in combination with the **M** value, flash point ($\mathbf{T_{flash}}$) and $\mathbf{T_b}$ values of the fluids (Eq. B-2-4 in Appendix B-2).

Table 2-6. Average Combustion Property Data for the Engine Compartment Fluids

Fluids	New/ Used	ΔH_v	ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}	y_{co}	y_{co2}	y_{sm}
1. Motor Oils Petroleum)	New	0.400	42.8	28.4	12.8	15.5	0.019	2.12	0.052
	Used	0.553	41.7	30.6	15.1	15.5	0.018	2.23	0.059
2. Motor Oils (synthetic)	New	0.369	42.3	28.7	12.7	16.1	0.016	2.16	0.044
	Used	0.565	41.2	27.4	11.6	15.8	0.014	2.04	0.071
3. Gear Lubrication Fluid	New	0.284	42.7	30.7	13.6	17.1	0.025	2.29	0.072
4. Power Steering Fluids	New	0.371	41.9	25.4	11.6	13.8	0.021	1.90	0.064
	Used	0.592	41.3	30.4	13.8	16.6	0.023	2.27	0.077
5. Automatic Transmission Fluids	New	0.486	42.6	25.8	11.5	14.3	0.020	1.92	0.061
	Used		42.9	32.4	15.1	17.3	0.024	2.41	-
6. Brake Fluids	New	0.574	25.7	22.0	12.9	9.1	0.004	1.66	<0.001
	Used	0.377	25.2	23.8	17.1	6.7	0.002	1.79	0.007
7. Antifreeze	New	0.754	19.9	16.1	9.8	6.3	0.005	1.21	0.006
8. Engine Coolants	New	1.387	No Ignition						
	Used	1.309	No Ignition						
9. Windshield Washing Fluids	New	1.326	16.9	10.9	3.8	3.8	0.008	0.89	0.010

2.3.4.7 Heat of Combustion and Yields of Products

The net complete, chemical, convective, and radiative heats of combustion and yields of products quantified for the engine compartment fluids are listed in Table B-3-18 in Appendix B-3. Literature values for other fluids are listed in Tables B-2-4, B-2-6, B-2-8, B-2-10, B-2-12, and B-2-13 in Appendix B-2. The heats of combustion for engine compartment fluids are very similar to the literature values for generically similar fluids.

The fire intensity is governed by the heat release rate and the contamination of the fire environment by the release rates of products, airflow rates and mixing of products and air. Heat release rate and generation rate of products depend on the heat of combustion, yields of products and release rate of the fluid vapors and/or droplets.

Burning of Fluids Released as Vapors and/or Liquid Droplet Sprays

For fluids burning as vapors and/or liquid droplet sprays, the heat release rate and generation rates of products are expressed as:

a) Heat release rate = mass flow rate of the fluid in the spray x heat of combustion;

b) Generation rate of a product = mass flow rate of the fluid in the spray x product yield ;

Burning of Fluids in Liquid Pools

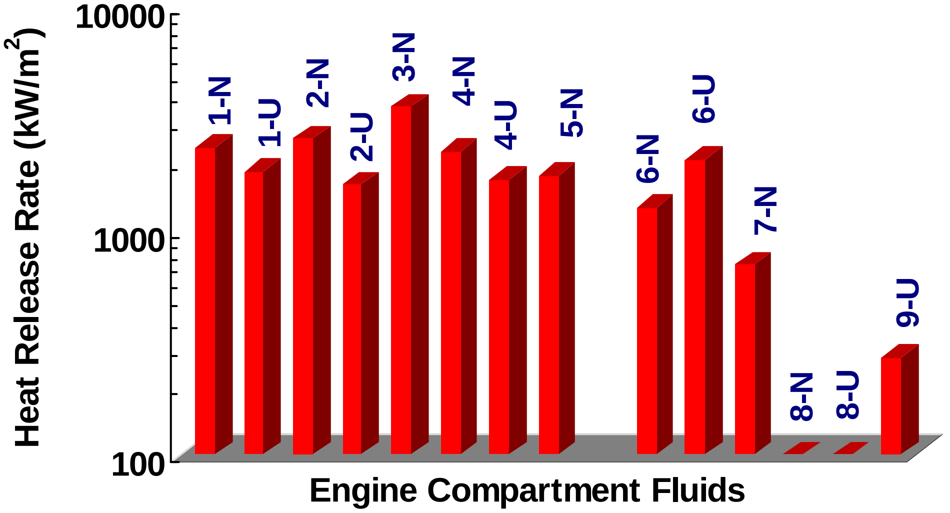
For fluids burning as liquid pool fires, the heat release rate and generation rates of products are expressed as:

- Release rate of fluid vapors: heat of vaporization ($\mathbf{\Delta H_v}$) of the fluid times the net heat flux from the flame to the surface ($\dot{\mathbf{q}}''_{\mathbf{n}}$) (Eq. B-2-11 in Appendix B-2);
- Heat release rate: release rate of fluid vapors time the heat of combustion ($\mathbf{\Delta H_{ch}}$) (Eqs. 12 in Appendix C-2) or Heat Release Parameter, **HRP** ($\mathbf{\Delta H_{con}/\Delta H_v}$) times $\dot{\mathbf{q}}''_{\mathbf{n}}$ (Eq. B-2-13 in Appendix B-2);
- Generation rates of products: release rate of fluid vapors time the product yields ($\mathbf{y_j}$) (Eq. B-2-14 in Appendix B-2) or Product Generation Parameter ($\mathbf{y_j/\Delta H_v}$) times $\dot{\mathbf{q}}''_{\mathbf{n}}$ (Eq. B-2-15 in Appendix B-2).

Results from various studies on large-scale pool fires of fluids indicate that $\dot{\mathbf{q}}''_{\mathbf{n}} \approx 33$ kW/m^2, irrespective of the generic nature of the fluids, leading to Eqs. B-2-19 and B-2-20 in Appendix B-2 and thus the quantified data for the fire properties of the engine compartment fluids can be used to estimate the maximum possible heat release rate and generation rates of the products expected in pool fires of the spilled fluids under the vehicle in crashes. These estimates are shown in Figs. 2-6 and 2-7.

The estimated heat release rates for the hydrocarbon based engine compartment fluids are higher than the rates for the non-hydrocarbon based fluids. The estimated heat release rates for the engine compartment fluids generically similar to other fluids are comparable, suggesting that hazards from the engine compartment fluids are expected to be similar to the hazards for other fluids.

The estimated generation rates of CO and smoke for the hydrocarbon based engine compartment fluids are significantly higher than for the non-hydrocarbon based fluids and are comparable to those for the generically similar fluids, data for which are reported in the literature. The estimates suggest that under similar scenarios, hydrocarbon based engine compartment fluids are expected to create more hazardous fire environments than the non-hydrocarbon based fluids.



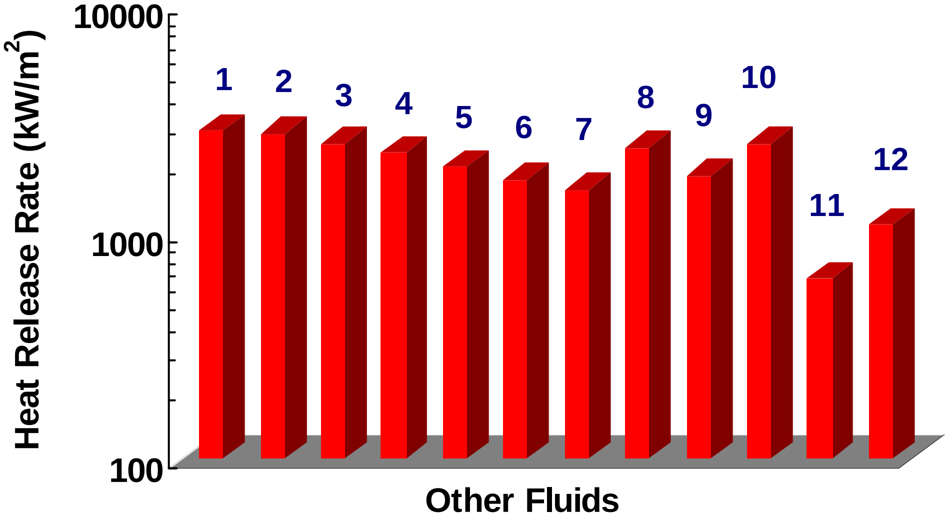
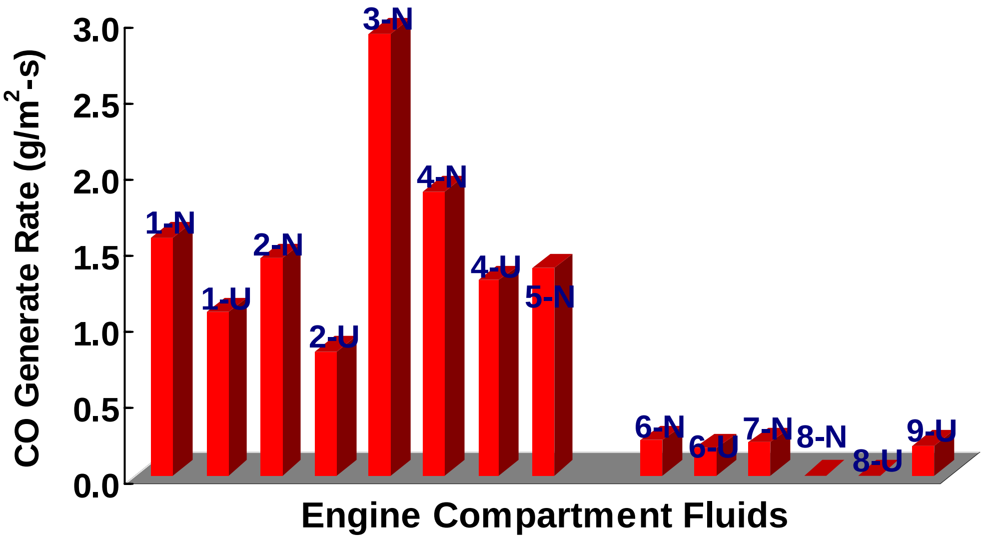


Figure 2-6. Estimated heat release rate for the engine compartment fluids and other fluids. N: new; U: used. Fluids are identified by numbers. The numbers for the engine compartment fluids are listed in Table 2-6 and for other fluids in Table B-2-2 in Appendix B-2.



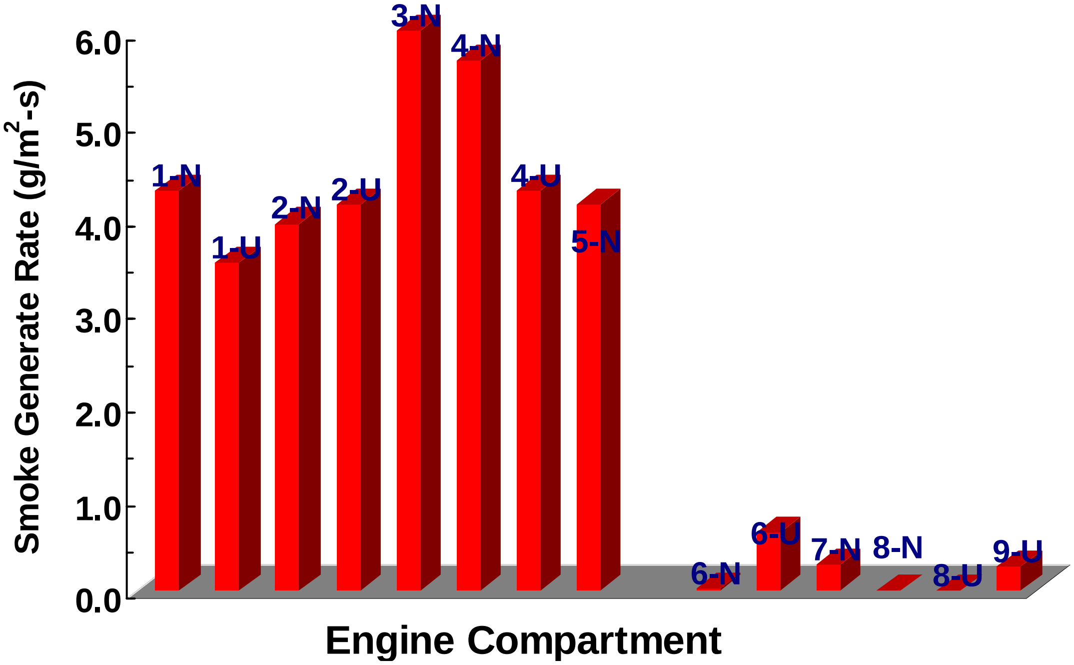


Figure 2-7 Estimated generation rates of CO and smoke for the engine compartment fluids. N: new; U: used. Numbers for the engine compartment fluids are listed in Table 3-5.

NOMENCLATURE

$\mathbf{a_j}$	Mass coefficient for product yield (g/g)
$\mathbf{b_j}$	Molar coefficient for the product yield (g/mole)
$\mathbf{c_p}$	Heat capacity (kJ/g-K)
$\mathbf{E_v}$	Vaporization energy (kJ/g)
$\mathbf{h_i}$	Mass coefficient for heat of combustion (kJ/g)
$\mathbf{\Delta H_{ch}}$	Chemical heat of combustion (kJ/g)
$\mathbf{\Delta H_{con}}$	Convective heat of combustion (kJ/g)
$\mathbf{\Delta H_{rad}}$	Radiative heat of combustion (kJ/g)
$\mathbf{\Delta H_T}$	Net heat of complete combustion (kJ/g)
$\mathbf{\Delta H_v}$	Heat of vaporization (kJ/g)
LFL	Lower flammability limit (%)
$\dot{\mathbf{m}}_\mathbf{f}''$	Release rate of vapors (g/m^2-s)
$\mathbf{m_i}$	Molar coefficient for heat of combustion (kJ/mole)
$\mathbf{M}$	Molecular weight (g/mole)
$\dot{\mathbf{q}}_\mathbf{f}''$	Flame heat flux per unit surface area (kW/m^2)
$\dot{\mathbf{q}}_\mathbf{n}''$	Net flam heat flux (kW/m^2)
$\dot{\mathbf{q}}_\mathbf{rr}''$	Surface re-radiation loss (kW/m^2)
$\dot{\mathbf{Q}}_\mathbf{ch}''$	Chemical heat release rate per unit surface area (kW/m^2)
$\mathbf{R}$	Universal gas constant (8.314 J/mole-K)
$\mathbf{s}$	Stoichiometric mass air-to-fuel ratio (g/g)
$\mathbf{t_R}$	Retention time of a fluid component in the GC column (min)
$\mathbf{T_a}$	Autoignition temperature (**AIT**) (^{o}C)
$\mathbf{T_b}$	Boiling point (^{o}C)
$\mathbf{T_{flash}}$	Flash point (^{o}C)
$\mathbf{T_{fire}}$	Fire Point (^{o}C)
$\mathbf{T_{fb}}$	Final boiling point (^{o}C)
$\mathbf{T_{ib}}$	Initial boiling point (^{o}C)
$\mathbf{T_{hot}}$	Hot surface ignition (^{o}C)
$\mathbf{T_{iv}}$	Initial vaporization temperature (^{o}C)
$\mathbf{T_o}$	Ambient temperature (^{o}C)
$\mathbf{T_{v,\ peak}}$	Peak vaporization temperature (^{o}C)
UFL	Upper flammability limit (%)
$\mathbf{y_j}$	Yield of product j (g/g)
ρ	Density (kg/m^3)
χ	Combustion efficiency
$\chi_{\mathbf{rad}}$	Radiative component of the combustion efficiency

REFERENCES

1. Britton, L.G. “Survey of Fire Hazard Classification Systems for Liquids”, *Process Safety Progress*, 18, 225-234, 1999.

2. Fire Hazard Properties of Flammable Liquids, Gases, and Volatile Solids, National Fire Protection Association (NFPA) Standard No. 325-1991.

3. Kanury, A. M., “Ignition of Liquid Fuels”, *The SFPE Handbook of Fire Protection Engineering*, Third Edition, Section 2, Chapter 2-8, pp. 2-188 to 2-199. The National Fire Protection Association Press, Quincy, MA. 2002.

4. Kuchta, J.M., “Investigation of Fire and Explosion Accidents in the Chemical, Mining, and Fuel-Related Industries”, United States Department of the Interior, Bureau of Mines Bulletin 680, 1986.

5. Gottuk, D.T., and White, D.A., “Liquid Fuel Fires”, *The SFPE Handbook of Fire Protection Engineering*, Third Edition, Section 2, Chapter 15, pp. 2-297 to 2-316. The National Fire Protection Association Press, Quincy, MA. 2002.

6. Beyler, C., “Fire Hazard Calculations for Large, Open Hydrocarbon Fires”, *The SFPE Handbook of Fire Protection Engineering*, Third Edition, Section 3, Chapter 11, pp. 3-268 to 3-314. The National Fire Protection Association Press, Quincy, MA. 2002.

7. ASTM Standard Test Methods. The American Society for Testing and Materials, Annual Books of ASTM Standards.

8. Santrock, J., “Flammability Properties of Engine Compartment Fluids Other than Gasoline-Gas Chromatography/Mass Spectroscopy Analysis”, www.nhtsa.dot.gov, Docket Number: 3588; Document Number: NHTSA-1998-3588-199, November 5, 2002.

9. Santrock, J., and Kononen, D.W., “Flammability Properties of Engine Compartment Fluids Other than Gasoline-Autoignition Characteristics of Non-Gasoline Motor Vehicle Fluids on Heated Surfaces”, www.nhtsa.dot.gov, Docket Number: 3588, Document Number: NHTSA-1998-3588-193, November 5, 2002.

10. Jodeh, S., and I. A. Abu-Isa, I., “ Determination of Boiling Point, Heat Capacity, and Heat of Vaporization for Engine Compartment Fluids Using Differential Scanning Calorimetry (DSC)” *Eighth International Polymer Characterization*, Denton, Texas, January 10-14, 2000.

11. Tewarson, A., “Thermophysical Properties and Fire Properties of Automobile Engine Compartment Fluids” Private Communication to GM, attention Dr. Douglas Kononen, January 2002.

12. Babrauskas, V., “Ignition of Liquids” Chapter 6, pp. 182-233, Ignition Handbook, Fire Sciences Publishers, Issaquah, WA, 2003.

13. Tewarson, A., “Generation of Heat and Chemical Compounds in Fires”, *The SFPE Handbook of Fire Protection Engineering*, Third Edition, Section 3, Chapter 4, pp. 3-82 to 3-161. The National Fire Protection Association Press, Quincy, MA. 2002.

14. Joulain, P., "The Behavior of Pool Fires: State of the Art and New Insights", *Twenty-seventh Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 2691-2706, 1998.

15. Drysdale, D., “An Introduction to Fire Dynamics”, John Wiley and Sons, New York, N.Y. 1985.

16. Koseki, H., "Large-Scale Pool Fires: Results of Recent Experiments", *Fire Safety Science-Proceedings of the Sixth International Symposium*, University of Poitiers, France, International Association for Fire Safety Science, pp. 115-132, 1999.

17. Koseki, H., "Combustion Properties of Large Liquid Pool Fires", Fire Technology, **25** (3), 241, 1989.

18. Burgess, D.S., Strasser, A., and Grumer, J., "Diffusive Burning of Liquid Fuels in Open Trays", *Fire Research Abstracts and Reviews*, **3,** 177, 1961.

19. Marlair, G., Cwiklinski, C., Marliere, F., Breulet, H., and Costa, " A Review of Large-Scale Fire Testing Focusing on the Fire Behavior of Chemicals”, Inteflam1996, Cambridge, U.K. 1996.

20. Tewarson, A., “Combustion efficiency and its Radiative Component”, *Fire Safety Journal*, **39**, 131-141, 2004.

21. Kirk-Othmer Encyclopedia of Chemical Technology, Fourth Edition, M. Howe-Grant, Editor), Volume 15, pp. 470-517, John Wiley and Sons, New York, N.Y. 1995.

22. Automotive Handbook, 2nd Edition, Robert Bosch GmbH, Stuttgart, Germany, 1986.

23. Handbook of Chemistry and Physics, 59th Edition, 1978-1979, CRC Press, West Palm Beach, Florida.

24. Maxwell, J.B., Data Book on Hydrocarbons, Application to Process Engineering, D.Van Nostrand Company, Inc., New York, N Y 1950.

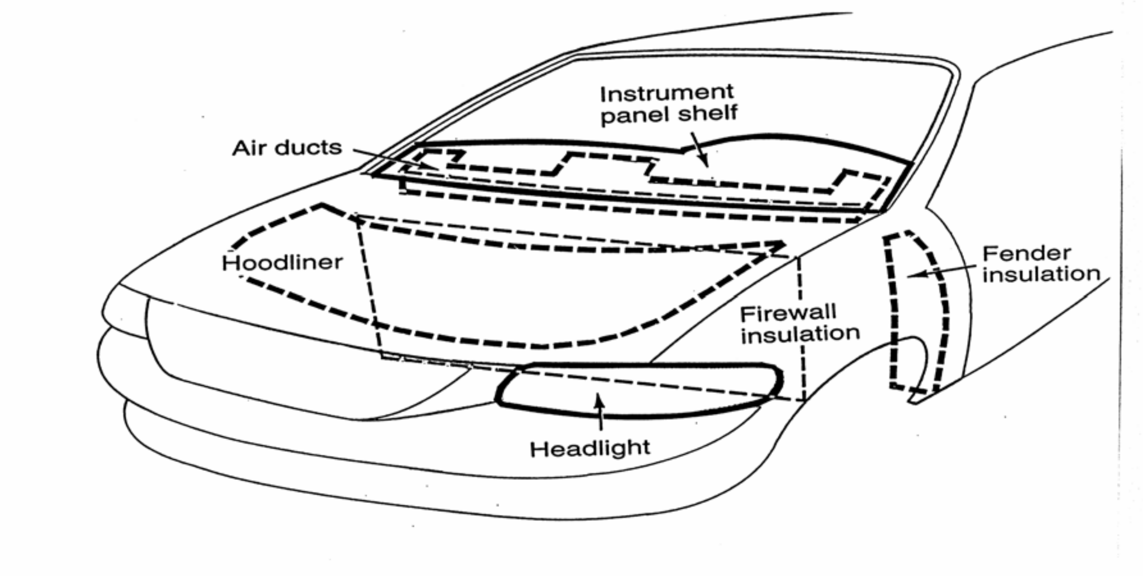
APPENDIX A-1

VEHICLE PARTS AND THEIR COMPOSITIONS
(References Chapter I)

A-1-1. INTRODUCTION

In the GM, NHTSA and MVFRI research projects, several plastics from parts from a 1996 Dodge Caravan and a 1997 Chevrolet Camaro were used in the mini-scale and small-scale tests. Fire tests were also performed using the vehicle parts as well as the entire vehicles. Some of the plastics in major parts of the vehicles are identified in Figures A-1-1 and A-1-2.

FRONT VIEW



SIDE VIEW

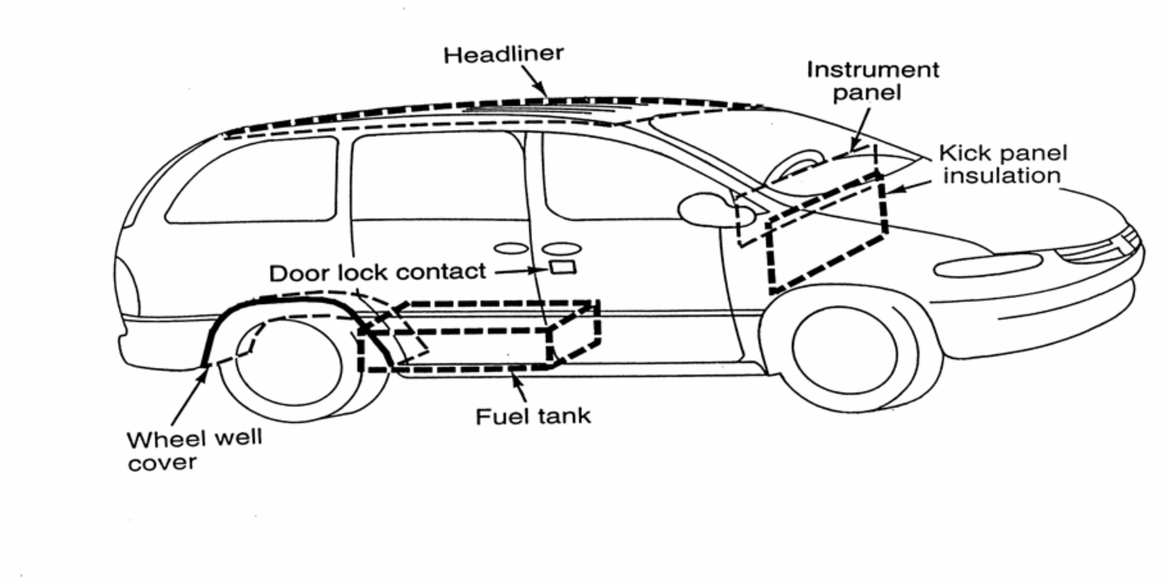


FIGURE A-1-1 Front and side view of a motor vehicle

TOP VIEW OF ENGINE COMPARTMENT

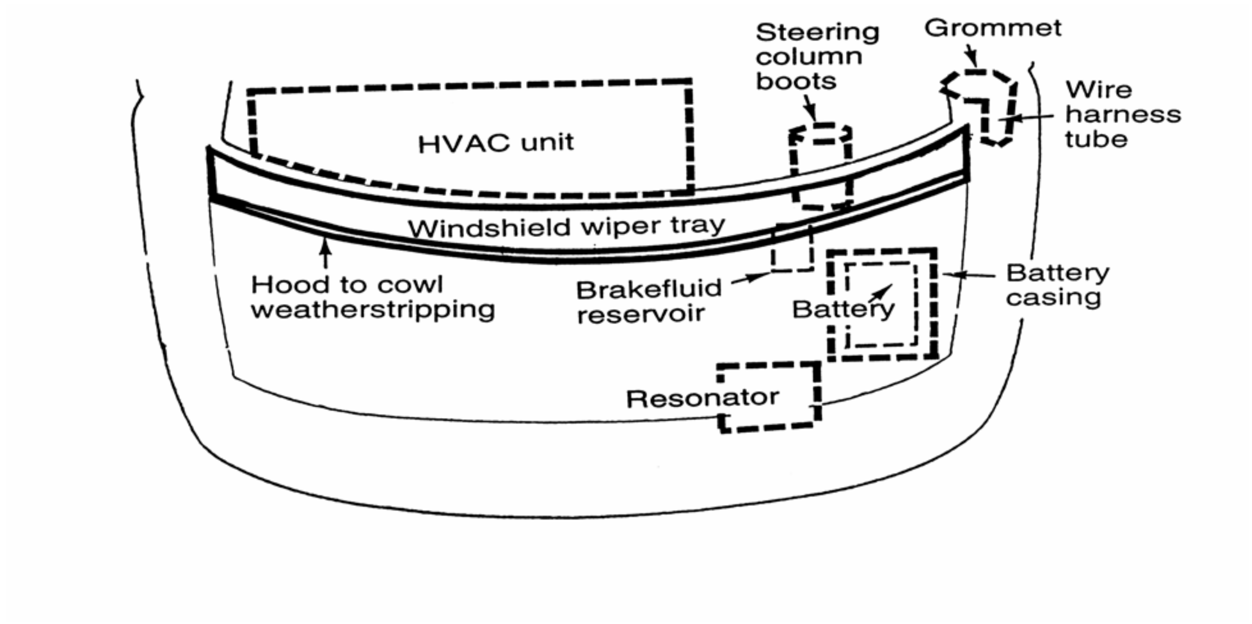


FIGURE A-1-2 Top view of the engine compartment of a motor vehicle.

The vehicle parts examined in the studies and their compositions are listed in Tables A-1-1 to A-1-7.

Table A-1-1 Plastics in a 1996 Dodge Caravan Parts [1]

Part	Description	Plastic	Weight (kg)
GJ42SK4A	headliner, backing - top layer, structural support	Polyethyleneterephthalate (PET)	
GJ42SK4B	headliner, high density foam - layer 3	Polyether urethane (PEU + methyldiisocyanate, MDI)	
GJ42SK4C	headliner, low density foam - layer 2	Polyester urethane (PESPU) with Surlyn film	
GJ42SK4D	headliner, fabric - exposed surface, bottom layer	Nylon 6	
GJ42SK4E	headliner, center-structural support	PET binder on glass	
Whole system			2.61
JF48SKA	instrument panel, foam - between structure and cover	PEU +MDI	
JF48SK5B	instrument panel, cover - exposed surface	Polyvinylchloride (PVC)	
JF48SKC	instrument panel, structure	Polycarbonate (PC)	
Whole system			3.61
PL98SX8A	instrument panel shelf, main panel	PC	
PL98SX8B	instrument panel shelf, foam - small seals	PEU	
Whole system			2.75
4612512A	resonator, structure,	Polypropylene (PP)	0.71
4612512B	resonator, intake tube	Ethylene-propylene-diene monomer (EPDM)	0.29
4612512C	resonator, effluent tube	EPDM	0.14
Whole system			1.14
4674711A	kick panel insulation, foam	Polyether urethane	
4674711B	kick panel insulation, backing	PVC	
Whole system			4.82
4678345A	air ducts, small ducts	Polyethylene (PE)	
4678345B	air ducts, large ducts	PP	
Whole system			4.26

Table A-1-1 continued on the next page

Table A-1-1 Continued from the previous page

Part	Description	Plastics	Weight (kg)
4680250A	steering column boot, inner interior boot	Natural rubber (NR)	0.04
4680250B	steering column boot, cotton shoddy	Mixture of cotton, polyester, and other fibers	0.02
4680250C	steering column boot, outer interior boot	Polyester co-polyester elastomer	0.10
Whole system			0.17
4683264A	brake fluid reservoir, reservoir	PP	0.67
4683264B	brake fluid reservoir, cap	PP	0.07
4707580A	wire harness tube, tube	PE	0.07
4707808A	door lock contact, wire coating		
4707808B	door lock contact, wire mesh - grouped wires		
4707743C	door lock contact, structure	Poly (acrylonitrile-butadiene-styrene), ABS	
4716051	windshield wiper tray, structure	Sheet molding compound (SMC)	3.40
4716345A	fender insulation, low density foam for sound reduction	Polystyrene (PS)	
4716345B	fender insulation, high density foam for sound reduction	PS	
Whole system			0.11
4716832A	hood liner, insulation (back)	PET, cellulose and epoxy	
4716832B	hood liner, face	PET	
Whole system			1.00
4716895	wheel well cover, fuel tank shield	PP	0.56
4734025	HVAC unit-door, foam covering		0.29
4734033	HVAC unit, door- for thermostat	PVC	0.08
4734039A	HVAC unit door, structure	Nylon 66	
4734039B	HVAC unit door, rubber seal	Thermoplastic polyolefin (TPO)	
4734041A	HVAC unit door, structure	Nylon 66	
4734041B	HVAC unit door, rubber seal	TPO	
Whole system			0.11

Table A-1-1 continued on the next page

Table A-1-1 continued from the previous page

Part	Description	Plastic	Weight (kg)
4734042A	HVAC unit door, structure		
4734042B	HVAC unit door, rubber seal		
Whole system			0.10
4734063	HVAC unit, cover	PP	
4734067A	HVAC unit seal, foam - heating coil entrance	ABS and PVC blend	
4734067B	HVAC unit seal, backing - heating coil entrance	Ethylene vinyl acetate (EVA)	
Whole system			0.05
4734071	HVAC unit , top main housing-contains coils, doors and fan	PP	0.87
4734072	HVAC unit, bottom main housing - contains coils, doors and fan	PP	1.61
4734073	HVAC unit, fan top cover	PP	0.29
4734074	HVAC unit, fan bottom cover	PP	0.11
4734080	HVAC unit, cover-for directional control	PP	
4734081	HVAC unit, deflector- for air flow	PP	0.09
4734225	HVAC actuator, casing	PP	0.15
4734367	HVAC unit, housing	PP	0.25
4734370	HVAC unit, seals - both large and small	ABS and PVC blend	0.04
4734396	HVAC unit, seal		
4734650	HVAC unit, seal		0.02
4734651	HVAC unit , seal		0.01
4734724	HVAC unit, defogger tube	TPO	0.03
4883140A	fuel tank, tank	PE	
4883140B	fuel tank, hoses	Nylon 12	
4883140C	fuel tank, threads/seal-for fuel pump	PE	
Whole system			8.48

Table A-1-1 continued on the next page

Table A-1-1 continued from the previous page

Part	Description	Plastic	Weight (kg)
4857041A	headlights, lens	PC	
4857041B	headlights, backing	PC	
4857041C	headlights, retainer	Polyacetal (polyoxymethylene, POM)	
4857041D	headlights, bulb support structure-halogen	Polyimide	
4857041E	headlights, leveling mechanism	PC	
Whole system			1.70
4364944A	battery casing, top	PE/PP blend	
4364944B	battery casing, sides and bottom	PE/PP blend	
5235267	battery cover	PP	0.36
Whole system			17.30
4675359A	hood to cowl weather stripping, foam	EPDM	
4675359B	hood to cowl weather stripping, foam , rubber base	EPDM	
Whole system			0.44
4716896A	Bulkhead insulation engine side, exterior/face	Mixed fibers: cotton, nylon 66, and glass	
4716896B	Bulkhead insulation engine side, insides	PVC coating over glass	
4716896C	Bulkhead insulation engine side, support structure	PVC-hydrocarbon elastomer	
Whole system			2.38
3009	grommet - wire harness cap for 3008	EPDM	

Table A-1-2 Organic and Inorganic Fillers in Plastics in a 1996 Dodge Caravan Parts [1]

Part	Plastic	Inorganic Filler		Organic Filler (%)	Density (g/cm^3)
		Type	%		
GJ42SK4A	PET	Si, Ca	37.5	0.02	0.69
GJ42SK4B	PU		0.6	0.10	0.10
GJ42SK4C	PU		0.6	0.01	0.06
GJ42SK4D	Nylon 6		1.4	0.03	1.20
JF48SK5A	PU		0.5	0.13	0.11
JF48SK5B	PVC	Si, Ca	8.0	0.09	1.20
JF48SK5C	PC		0.4	0.10	1.12
PL98SX8A	PC		0.2	0.16	1.18
PL98SX8B	PU	S, Sr, Ba	37.3	0.00	0.09
3009	EPDM		1.9	0.49	1.21
4364944A	PE/PP blend		0.3	0.00	0.91
4364944B	PE/PP blend		0.3	0.00	0.88
4612512A	PP		20.4	0.01	1.06
4612512B	EPDM	Si, Ca	1.9	0.43	1.15
4612512C	EPDM		1.7	0.45	1.16
4674711A	PU	Si, S, Ba	11.0	0.00	0.02
4674711B	PVC	Si, S, Ca, Ba ($CaCO_3$, $BaSO_4$)	52.9		1.95
4675359A	EPDM	Mg, Si, S, Ca, Zn ($CaCO_3$, talc)	15.9	0.21	0.44
4675359B	EPDM	$CaCO_3$	14.6	0.32	0.41
4678345A	PE		0.0	0.01	0.95
4678345B	PP	Mg, Si (talc)	18.8	0.03	1.04
4680250A	Natural rubber	Si, S, Ca, Zn	7.7	0.33	1.26
4680250B	Fibers		2.9	0.16	0.22
4680250C	Polyester	Si, Ca, S	18.1	0.01	1.15
4683264A	PP		0.0	0.00	0.90
4683264B	PP		0.8	0.00	0.90
4707580	PE		0.3	0.00	0.95
4707808A		Al	35.8	0.00	1.16
4707808B			2.3	0.09	1.10
4707743C	ABS		4.4	0.00	1.07
4716051	SMC	Mg, Al, Si, Ca (glass fibers, $CaCO_3$)	47.2	0.04	1.64
4716345A	PS	Na, Mg, Al, Si, Ca, Zn (Kaolin)	32.8	0.02	0.90

Table A-1-2 continued on the next page

Table A-1-2 continued from the previous page

Part	Plastic	Inorganic Filler		Organic Filler (%)	Density (g/cm^3)
		Type	%		
4716345B	PS	Al, Si, Ti, Zn (Kaolin)	39.0	0.03	1.30
4716832A	PET, cellulose and epoxy	Mg, Si, S, Ca, Cu, Zn (silicate)	2.4	0.30	0.09
4716832B	PET	Mg, Si, Ca, Sb	1.3	0.31	0.66
4716895	PP		2.2	0.02	0.93
4716896A	Mixed fibers	Al, Si, S (glass)	7.9	0.17	1.60
4716896B	PVC	Mg, Al, Si, Ca, Ti, Ba (glass, $CaCO_3$, Kaolin)	44.9	0.04	1.00
4716896C	PVC-Hydrocarbon		42.0	0.01	1.60
4734025			0.2	0.07	0.11
4734033	PVC		15.6	0.23	1.38
4734039A	Nylon 66		37.3	0.02	1.46
4734039B	TPO		11.1	0.01	0.93
4734041A	Nylon 66		39.3	0.00	1.50
4734041B	TPO		13.6	0.01	0.97
4734042A			39.2	0.05	1.50
4734042B			12.5	0.02	0.98
4734063	PP	Mg, Si (talc)	36.1	0.02	1.19
4734067A	ABS/PVC	$CaCO_3$	16.9	0.14	0.10
4734067B		talc	16.8	0.47	2.10
4734074	PP	talc	36.1	0.00	1.21
4734225	PP		30.4	0.00	1.11
4734367	PP		35.2	0.00	1.20
4734370	ABS /PVC		18.5	0.14	0.07
4734396					0.12
4734650					0.11
4734651					0.17
4734724	TPO				0.97
4883140A	PE		0.0	0.00	0.94
4883140B	Nylon 12		0.4	0.00	1.04
4883140C	PE		0.3	0.00	0.95
4857041A	PC		0.2	0.18	1.19
4857041B	PC		0.2	0.21	1.20
4857041C	POM		0.2	0.00	1.41
4857041D	Polyimide		30.2	0.25	1.59
4857041E	PC		0.0	0.19	1.18
5235267	PP		0.2	0.01	0.90

Table A-1-3. Base Plastics and Additives in a 1997 Chevrolet Camaro Parts [5]

No.	Part Description	Base Plastic and Additive
1	Front bumper fascia	Polyurethane
2	Front bumper fascia lower deflector	Propylene-ethylene copolymer
3	Headlamp support panel	Propylene-ethylene copolymer
4	Rear bumper fascia	Polyurethane
5	Rear bumper fascia energy absorber	Polyethylene
6	Rear bumper impact bar	Polypropylene
7	Front wheelhouse panel liner	Propylene-ethylene copolymer
8	Hood insulator- backing	Polyethylene
9	Hood insulator- fiber	Glass fiber / phenolic binder
10	Hood insulator - scrim	Nylon 6 (benzoic acid)
11	Air inlet screen	Propylene-ethylene copolymer
12	Radiator inlet tank	Nylon 6/6 (organic-Cu compound)
13	Engine coolant fan shroud	Nylon 6/6
14	Radiator upper mounting panel	Nylon 6/6
15	Radiator air lower deflector	Propylene-ethylene copolymer
16	Radiator air lower baffle	Propylene-ethylene copolymer
17	Radiator air upper baffle	Propylene-ethylene copolymer
18	Air cleaner housing cover	Propylene-ethylene copolymer
19	Air cleaner outlet duct	Nylon 6
20	Mass air flow sensor	Propylene-ethylene copolymer
21	Air cleaner outlet rear duct	Ethylene-propylene-butadiene copolymer
22	Brake master cylinder reservoir	Propylene-ethylene copolymer
23	Power steering fluid reservoir	Nylon 6/6
24	Battery storage tank	Propylene-ethylene copolymer
25	ABS/TCS relay cover	Propylene-ethylene copolymer
26	Wire conduit	Propylene-ethylene copolymer
27	Windshield wiper blade	Polyisoprene
28	Windshield wiper arm	Polyethyleneterephthalate polyester
29	Windshield wiper arm finishing cap	Styrene-ethylene-butane copolymer
30	Windshield inner-layer	Polyvinyl butyral, dihexyl dipate, tinuvinP
31	Windshield washer solvent container	Polyethylene
32	Instrument panel compartment - front panel	Polypropylene
33	Instrument panel compartment- box	Propylene-ethylene copolymer
34	Instrument cluster- lens	Styrene/acrylonitrile copolymer

Table A-1-3 continued on the next page

Table A-1-3 continued from the previous page

No.	Part Description	Base Plastic and Additive
35	Instrument cluster- housing	Acrylonitrile-butadiene-styrene copolymer
36	Instrument cluster- housing	Polystyrene-phenolic resin
37	Instrument panel cluster trim plate	Styrene/acrylonitrile copolymer
38	Instrument panel-skin	Acrylonitrile-butadiene-styrenecopolymer bis(2-ethylhexyl phthalate)
39	Instrument panel - foam	Polyurethane
40	Instrument panel - structure	Polystyrene
41	Instrument panel upper trim panel	Poly(bis-phenol A carbonate)
42	Dash sound barrier - film	Polyethylene
43	Dash sound barrier - foam	Urethane, triphenyl phosphate
44	Windshield defroster nozzle and air distributor	Polypropylene
45	Dash panel insulator-film	Polyethylene
46	Dash panel insulator- foam	Polyurethane
47	Instrument panel driver knee bolster	Polypropylene
48	Front floor console door	Propylene-ethylene copolymer
49	Steering wheel inflatable restraint module - cover	Polyvinylchloride
50	Steering wheel inflatable restraint module - air bag	Nylon 6/6 with neoprene coating
51	Instrument panel inflatable restraint module - air bag	Nylon 6/6
52	HVAC module rear case	Polypropylene
53	HVAC module auxiliary A/C evaporator and blower lower case	Polyester, diallylphthalate C_{16} and C_{18} acid derivates
54	HVAC module vent mode valve - foam	Polyurethane
55	Front side door trim panel insert	Propylene-ethylene copolymer
56	Front side door trim panel map pocket	Propylene-ethylene copolymer
57	Front side door trim panel armrest - skin	Polyvinyl chloride, phthalate esters
58	Front side door trim panel armrest - foam	Polyurethane
59	Front side door trim panel - carpet upper	Polyethylene terphthalate polyester
60	Front side door trim panel - carpet lower	Nylon 6

Table A-1-3 continued on the next page

Table A-1-3 continued from the previous page

No.	Part Description	Base Plastic and Additive
61	Front seat cushion - sew pad	Urethane/styrene/acrylonitrile
62	Front seat cushion - pad	Urethane/styrene/acrylonitrile
63	Front seat cushion - cover seating area	Polyethyleneterphthalate polyester
64	front seat cushion bottom cover & rear seatback back cover	Polypropylene
65	Rear seat cushion - backing	Polyethyleneterphthalate polyester, glutaric acid di-N-butyl eater
66	Rear seat cushion cover - seating area	Polyethyleneterphthalate polyester
67	Rear seat cushion cover - side panels	Polypropylene
68	Seat belt	Polyethyleneterphthalate polyester
69	Floor carpet - pile	Nylon 6
70	Floor carpet - weave	Polyethyleneterphthalate polyester
71	Floor carpet - backing	Polyethylene
72	Floor pan drain hole plug	Ethylene-propylene-butadiene copolymer, benzothiazole 2-(2-butoxyethoxy)ethanol
73	Headlining trim finish panel - substrate	Glass fiber with novolac binder
74	Headlining trim finish panel - foam	Polyurethane
75	Headlining trim finish panel - fabric	Nylon 6
76	Quarter inner trim finishing panel	Propylene-ethylene copolymer
77	Fuel tank filler pocket	Propylene-ethylene copolymer
78	Rear compartment carpet - backing	Polyethyleneterphthalate polyester/polypropylene
79	Rear compartment carpet - pile	Polyethyleneterphthalate polyester
80	Rear speaker - seal	Polyurethane
81	Rear speaker - screen	Polyethyleneterphthalate polyester/polypropylene
82	Rear speaker - grille	Propylene-ethylene copolymer
83	Rear end spoiler	Polyester
84	Rear compartment lift window panel	Polyester
85	Rear compartment lift window inner panel cover	Propylene-ethylene copolymer
87	Rear compartment lift window weather strip	Propylene-ethylene copolymer, diphenyl ether
88	Rear compartment lift window closeout panel assembly-backing	Polyethyleneterphthalate polyester
89	Rear compartment lift window closeout panel assembly-binder	Polypropylene
90	Rear compartment lift window closeout panel assembly- felt	Nylon 6

Table A-1-4 Plastics in a 1997 Chevrolet Camaro Parts [4]

Part	Description	Plastic	Mass (kg)
10132027A	Windshield laminate	Polyvinyl butyral/polyvinyl alcohol	
10132027B	Windshield washer reservoir	PE	
10138735	Heating and Ventilation, side window defogger - outlet duct	Ethylene-Vinyl Acetate copolymer	0.04
10153750	Heating and Ventilation, floor air outlet distributor - duct	PP/PE copolymer	0.13
10208798	Floor drain plug, - structure	Hydrocarbon Plastic (EPR or EPDM)	0.01
10229657	Radiator air lower deflector	PP/PE copolymer	
10231299	Bumpers, Rear bumper fascia - structure	PU (Polyurethane – MDl/poly(2-propylene glycol))	6.18
10242723	Radiator air lower baffle	PP/PE copolymer	
10243962	Radiator and Engine Cooling, Radiator air upper baffle	PP/PE copolymer	0.56
10244975A	Radio speaker grille fiber film	PET/PP binder	
10244975B	Radio speaker grille	PP/PE copolymer	
10246204A	Body Front End, Cowl air inlet (left) - seal	PP/PE copolymer	
10246204B	Body Front End, Cowl air inlet (left) - Structure	PP/PE copolymer	
10246274	Front bumper fascia lower deflector	PP/PE copolymer	
10248339	Rear compartment lift window inner panel cover	PP/PE copolymer	
10253519	Rear end spoiler	SMC	
10253673	Quarter inner trim finishing panel	PP/PE copolymer	
10267995	Fuel tank filler pocket	PP/PE copolymer	
10269100A	Instrument Panel and Gages, Instrument panel - structure	Polystyrene	9.06
10269100B	Instrument Panel and Gages, Instrument panel - padding	Acrylonitrile butadiene Copolymer	
10269100C	Instrument Panel and Gages, Instrument panel - covering	Acrylonitrile butadiene Styrene TerPlastic (ABS)	2.31
10269102A	Instrument Panel and Gages, Instrument panel upper trim panel - structure	Styrene/acrylonitrile copolymer	
10269102B	Instrument Panel and Gages, Instrument panel upper trim panel - seals	Ethylene-Vinyl Acetate Copolymer	

Table A-1-4 continued on the next page

Table A-1-4 continued from the previous page

Part	Description	Plastic	Mass (kg)
10269102C	Instrument Panel and Gages, Instrument panel upper trim panel - seal film		
10270975	Dash sound barrier top layer (RH)	PE	
10273234A	Hood insulator top	PE	
10273234B	Hood insulator media	Phenol/formaldehyde/glass fiber	
10273234C	Hood insulator scrim	Nylon6/PMMA/phenolic	
10273748A	Front floor console door	PP/PE copolymer	
10273748B	Driver air bag	Nylon 6/6/neoprene coating	
10273748C	Passenger air bag	Nylon 6/6	
10274341	Instrument panel cluster trim plate	Styrene/acrylonitrile copolymer (SA)	
10277295A	RH front side door interior trim panels	PP/PE copolymer	
10277295B	LH front door interior trim panel	PP/PE copolymer	
10277295C	Front door map pocket	PP/PE copolymer	
10277446A	Heating and ventilation, distributor, windshield defroster nozzle – duct	PP	
10277446B	Heating and Ventilation, Distributor, windshield defroster nozzle - seal		
10277466	Heating and Ventilation, main instrument panel ventilation ducts - ducts and supporting structure	PP	2.37
10277772A	Interior trim, Headliner trim finish panel assembly – covering	Nylon 6	
10277772B	Interior trim, Headliner trim finish panel assembly – interior foam	PU	
10277772C	Interior trim, Headliner trim finish panel assembly - structural backing (yellow)	Phenolic resins	
10278015A	Body Front End, Hood insulator - black fibrous structure	Nylon 6 and Phenolic Binder (Novalac)	0.62
10278015B	Body Front End, Hood insulator - insulating fibers	Phenolic Binder (Novalac)	

Table A-1-4 continued on the next page

Table A-1-4 continued from the previous page

Part	Description	Plastic	Mass (kg)
10278989A	Body Rear End, Rear compartment lift window closeout panel assembly –carpet like coating	Nylon 6	1.80
10278989B	Body Rear End, Rear compartment lift window closeout panel assembly -structure	PP	
10278989C	Rear compartment lift window panel	SMC	
10278989D	Rear compartment lift window closeout panel assembly – fabric surface	PET	
10282257A	Instrument Panel and Gages, Dash sound barrier - black plastic	Polyethylene and Vinyl Acetate copolymer	5.73
10282257B	Instrument Panel and Gages, Dash sound barrier - insulating foam	PU	
10280337	RH headlamp support panel	PP/PE copolymer	
10280338	LH headlamp support panel	PP/PE copolymer	
10282914A	Rear compartment carpet backing	PET/PP binder	
10282914B	Rear compartment carpet surface	PET	
10284967	Body front end, front fender - structure	Styrene cross linked polyester	3.27
10286360	Instrument panel drive knee bolster	PP	
10288156	Radiator upper mounting panel	Nylon 6/6	
10290204A	Floor carpet surface	Nylon 6	
10290204B	Floor carpet binder	PE/PET	
10290204C	Floor carpet backing	PE	
10296525 &26	Body front end, front wheelhouse panel liner (right & left) – structure	PP/PE copolymer	1.11
11515174	Foam around radio rear speaker	PU	
12530564	Seat belt	PET	

Table A-1-4 continued on the next page

Table A-1-4 continued from the previous page

Part	Description	Plastic	Mass (kg)
16215781A	Instrument Panel and Gages, Instrument cluster - black housing	ABS	
16215781 B	Instrument Panel and Gages, Instrument dust - white housing	PS/phenolic resin	
16215781C	Instrument Panel and Gages, Instrument cluster - clear housing	Styrene/acrylonitrile copolymer	
16514312	Bumpers, Rear bumper fascia energy absorber - structure	Ethylene-Vinyl Acetate Copolymer	4.46
16524838	Bumpers, Headlamp support panel - structure	PP/PE copolymer	1.93
16632714	RH door carpet upper section	PET	
16632715A	LH door carpet lower section	Nylon 6	
16632715B	LH door carpet upper section	PET	
16632715C	RH door carpet lower section	Nylon 6	
16633455	Interior Trim, Quarter inner trim finishing panel	PP/PE copolymer	
16795366	Seats, Rear seatback cushion - formed foam	PU	
16795385A	Seats, Rear seatback back cover - foam	PP	
16795385B	Seats, Rear seatback back cover	PP	
16795385C	Seats, Rear seatback back cover	PET	
16795385D	Fiber cover under seat cushion	PP	
17997632A	Instrument panel compartment front door	PP	
17997632B	Instrument panel compartment rear section	PP/PE copolymer	
18020021	Brake master cylinder reservoir	PP/PE copolymer	
20294219	Rear bumper impact bar	PP	
22098787	Radiator and engine Cooling, Engine coolant fan	Nylon 6/6	0.43
22121694	Windshield wiper blade	Polyisoprene	
22154388 & 89	Windshield wiper support arm (RH & LH)	PET	
22154389B	Windshield wiper arm seal	Styrene/ethylene/butene copolymer	
25147156A	Air cleaner manifold air filter	PP/PE copolymer	

Table A-1-4 continued on the next page

Table A-1-4 continued from the previous page

Part	Description	Plastic	Mass (kg)
25147156B	Air cleaner manifold elbow	Nylon 6	
25147156C	Air cleaner manifold mass air filter sensor	PP/PE copolymer	
25147156D	Air cleaner manifold boot	EPDM	
26024352	Fluid reservoirs, power steering fluid reservoir	Nylon 6/6	0.27
52458712	Heating and ventilation, case heater cover (RR) – structure		0.24
52458713	Heating and ventilation, case air distributor front	PP	0.62
52458898	Heating and Ventilation, case, shroud (temp valve)	PP	0.43
52458938	Heating and Ventilation, heater front case seal	PU	0.04
52458941	Heating and Ventilation, heater core shroud seal	PU	0.01
52458960	Heating and Ventilation, case heater (RR)	PP	
52458961A	Heating and Ventilation, heater core tube seal - Dark foam	PU	
52458961B	Heating and Ventilation, heater core tube seal - Light colored foam		
52458965	Heating and Ventilation, A/C evaporator and upper blower case - structure	PP	0.57
52458972	Heating and Ventilation, A/C evaporator seal	PU	
52458976	Heating and Ventilation, case aux a/c evaporator and blower lower	PU	1.76
52461468A	Heating and Ventilation, Case, mode with valve inlet and outlet - door (white)	Nylon 6,6	0.38
52461468B	Heating and Ventilation, Case, mode with valve inlet and outlet – Housing (black)	PP	
52461468C	Heating and Ventilation, Case, mode with valve inlet and outlet - seal	PP/PE copolymer	
52461468D	Heating and Ventilation, Case, mode with valve inlet and outlet - seal	PP/PE copolymer	
52464968	Heating and Ventilation, seal, air distributor case		0.04

Table A-1-4 continued on the next page

Table A-1-4 continued from the previous page

Part	Description	Plastic	Mass (kg)
52465340	Fluid reservoirs, Radiator outlet tank - structure	Nylon 6/6	0.41
52472378	Heating and Ventilation, valve mode - seal	PU	0.22
62019594A	Power steering fluid reservoir	Nylon 6/6	
62019594B	Battery storage tank	PP/PE copolymer	
62019594C	ABS/TCS Relay cover	PP/PE copolymer	
62019594D	Wire harness wrap	PP/PE copolymer	

Table A-1-5. Inorganic Fillers and Organic Residue in Plastics in a 1997 Chevrolet Camaro Parts [4]

Part	Description	Inorganic Filler		Organic Residue (%)	Density (g/cm^3)
		Type	%		
1038735	Heating and Ventilation, side window defogger - outlet duct		0.2	0	0.80
1053750	Heating and Ventilation, floor air outlet distributor - duct		17.4	0	1.04
10208798	Floor drain plug, - structure	Si	3.1	43	1.19
10231299	Bumpers, Rear bumper fascia - structure		3.5	20	1.04
10243962	Radiator and Engine Cooling, Radiator air upper baffle		0.2	1	0.88
10246204A	Body Front End, Cowl air inlet (left)-seal		1.6	0	1.14
1046204B	Body Front End, Cowl air inlet (left)-structure		1.1	2	0.89
1069100A	Instrument Panel and Gages, Instrument panel - structure		21.0	0	0.96
1069100B	Instrument Panel and Gages, Instrument panel - padding		0.3	8	0.06
10269100C	Instrument Panel and Gages, Instrument panel - covering		5.0	21	0.89
10269102A	Instrument Panel and Gages, Instrument panel upper trim panel - structure		1.2	18	1.18
10269102B	Instrument Panel and Gages, Instrument panel upper trim panel - seals		0.7	0	0.04
10269102C	Instrument Panel and Gages, Instrument panel upper trim panel - seal film		1.5	1	0.03
10277446A	Heating and Ventilation, Distributor, windshield defroster nozzle - duct		17.6	2	1.05
10277446B	Heating and Ventilation, Distributor, windshield defroster nozzle - seal		22.8	0	0.04

Table A-1-5 continued on the next page

Table A-1-5 continued from the previous page

Part	Description	Inorganic Filler		Organic Residue (%)	Density (g/cm^3)
		Type	%		
10277466	Heating and Ventilation, main instrument panel ventilation ducts - ducts and supporting structure		21.0	0	1.07
10277772A	Interior trim, Headliner trim finish panel assembly - covering		1.8	2	0.09
10277772B	Interior trim, Headliner trim finish panel assembly - interior foam		2.3	4	0.03
10277772C	Interior trim, Headliner trim_ finish panel assembly - structural backing (yellow)		82.0	3	0.16
10278015A	Body Front End, Hood insulator - black fibrous structure		3.2	17	0.06
10278015B	Body Front End, Hood insulator - insulating fibers		74.8	15	0.08
10278989A	Body Rear End, Rear compartment lift window closeout panel assembly –carpet like coating	talc	1.6	11	0.27
10278989B	Body Rear End, Rear compartment lift window closeout panel assembly -structure		4.8	6	1.14
10282257A	Instrument Panel and Gages, Dash sound barrier - black plastic		31.3	0	1.20
1082257B	Instrument Panel and Gages, Dash sound barrier - insulating foam		1.7	0	0.05
10284967	Body Front End, Front Fender - structure		21.5	5	1.20
10296526	Body Front End, Front wheelhouse panel liner (left) - structure		0.1	1	0.88
16215781A	Instrument Panel and Gages, Instrument cluster-black housing		0.1	2	1.43
16215781 B	Instrument Panel and Gages, Instrument cluster - white housing		9.6	11	1.36
16215781C	Instrument Panel and Gages, Instrument cluster - clear housing		0.1	0	1.11
16514312	Bumpers, Rear bumper fascia energy absorber - structure		0.4	0	0.99
16524838	Bumpers, Headlamp support panel -structure		46.5	0	1.11
16633455	Interior Trim, Quarter inner trim finishing panel		0.8	14	0.95
16795366	Seats, Rear seatback cushion - formed foam		0.5	4	0.05
16795385A	Seats, Rear seatback back cover - foam		10.6	0	1.23
16795385B	Seats, Rear seatback back cover		2.6	9	1.17
16795385C	Seats, Rear seatback back cover		1.4	0	0.02

Table A-1-5 continued on the next page

Table A-1-5 continued from the previous page

Part	Description	Inorganic Filler		Organic Residue (%)	Density (g/cm^3)
		Type	%		
22098787	Radiator and Engine Cooling, Engine coolant fan	talc/glass fibers	35.5	3	1.44
26024352	Fluid reservoirs, Power steering fluid reservoir	kaolin	33.0	5	1.40
52458712	Heating and Ventilation, case heater cover (RR) - structure		38.1	0	1.20
52458713	Heating and Ventilation, case air distributor front		38.3	0	1.20
52458898	Heating and Ventilation, case, shroud (temp valve)		37.9	0	1.17
52458938	Heating and Ventilation, heater front case seal	kaolin	38.4	1	0.18
52458941	Heating and Ventilation, heater core shroud seal	kaolin	34.7	1	0.21
52458960	Heating and Ventilation, case heater (RR)		39.6	1	1.23
52458961A	Heating and Ventilation, heater core tube seal - Dark foam	kaolin	46.2	7	0.09
52458961B	Heating and Ventilation, heater core tube seal - Light colored foam	kaolin	38.9	3	0.05
52458965	Heating and Ventilation, A/C evaporator and upper blower case - structure	talc	38.1	0	1.22
52458972	Heating and Ventilation, A/C evaporator seal	kaolin	36.9	3	0.11
52458976	Heating and Ventilation, case aux a/c evaporator and blower lower	kaolin	43.3	1	1.71
52461468A	Heating and Ventilation, Case, mode with valve inlet and outlet - door (white)	silica	38.2	1	1.48
52461468B	Heating and Ventilation, Case, mode with valve inlet and outlet - Housing (black)		20.7	1	1.07
52461468C	Heating and Ventilation, Case, mode with valve inlet and outlet - seal	calcium carbonate	20.9	1	1.20
52461468D	Heating and Ventilation, Case, mode with valve inlet and outlet - seal		0.3	1	0.86
52464968	Heating and Ventilation, seal, air distributor case		0.7	1	0.04
52465340	Fluid reservoirs, Radiator outlet tank, structure		25.3	2	1.18
52472378	Heating and Ventilation, valve mode-seal		19.7	2	0.03

Table A-1-6. Base Plastics and Additives in a 1997 Ford Explorer Parts [6]

No.	Part Description	Base Plastic and Additive
1	Front bumper fascia	Polypropylene
2	Front bumper valance panel	Polypropylene
3	Radiator grille - A	Acrylonitrile-butadiene-styrene copolymer
4	Radiator grille - B	Polypropylene
5	Radiator- upper sight shield	Polypropylene
6	Radiator-fan shroud	Polystyrene
7	Radiator - air deflector	Propylene-ethylene copolymer
9	Radiator-coolant recovery reservoir	Polypropylene
10	Radiator-fan blades	Polypropylene
11	Windshield washer fluid reservoir	Polyethylene
12	Windshield inner-layer	Polyvinyl butyral
13	Rocker panel trim molding	Propylene-ethylene copolymer
14	Front door rocker step pad	Propylene-ethylene copolymer
15	Rear bumper stone deflector	Propylene-ethylene copolymer
16	Lift gate scuff plate	Propylene-ethylene copolymer
17	Rear lamp assembly - lens	Polymethylmethacrylate
18	Battery cover	Propylene-ethylene copolymer
19	Engine compartment wire conduit	Nylon6-polyethylene
20	Power distribution box-cover	Polybutyleneterphthalate
21	Power distribution box-housing	Phenol-formaldehyde copolymer
22	Engine air cleaner housing	Propylene-ethylene copolymer
23	Instrument panel-cover	PVC, phthalate esters
24	Instrument panel-foam padding	Polyurethane
25	HVAC module	Polypropylene
26	HVAC-vents	Propylene-ethylene copolymer
27	HVAC-ducts	Polypropylene or polypropylene-polyethylene
28	Roof trim panel-cover	Nylon 6
29	Roof trim panel-foam	Polyurethane
30	Roof trim panel-substrate	Glass fiber with phenolic binder
31	Front seat cushion-sew pad	Urethane-styrene-acrylonitrile, phenolics
32	Front seat cushion-pad	Urethane-styrene-acrylonitrile, phenolics
33	Front seat cushion-cover seating area	Polyethyleneterphthalate, triphenyl phosphate

Table A-1-6 continued on the next page

Table A-1-6 continued from the previous page

No.	Part Description	Base Plastic and Additive
34	Front seat back-cover seating area	Polyethyleneterphthalate, triphenyl phosphate
35	Front seat back-sew pad	Urethane-styrene-acrylonitrile, phenolics
36	Front seat back-pad	Urethane-styrene-acrylonitrile, phenolics
37	Front seat back-cover rear surface	Polyvinylchloride, diisononyl phthalate
38	Front seat back-cover rear backing	Polyethyleneterphthalate
39	Front seat back-cover rear-pad	Urethane-styrene-acrylonitrile, phenolics
40	Front seat-track trim cover	Propylene-ethylene copolymer
41	Seat belt	Polyethyleneterphthalate
42	Floor carpet-pile	Propylene-ethylene copolymer
43	Floor carpet-weave	Propylene-ethylene copolymer
44	Floor carpet-backing	Polyethylene
45	Floor panel drain hole plug	Ethylene-propylene-butadiene copolymer
46	Floor console	Acrylonitrile-butadiene-styrene copolymer
47	Floor console-internal support	Polystyrene
48	Floor console-distribution duct	Propylene-ethylene copolymer
49	Floor console-blower housing	Polypropylene
50	Floor console-vent duct	Polypropylene
51	Floor console-rear bezel	Poly (bisphenol A carbonate)
52	Rear door trim panel-A	Polyvinylchloride, phthalate esters
53	Rear door trim panel-B	Polyvinylchloride, phthalate esters
54	Rear door trim panel-C	Acrylonitrile-butadiene-styrene copolymer
55	Rear door trim panel-D	Polypropylene
56	Rear door trim panel-E	Poly(bisphenol A carbonate)
57	Rear door trim panel-F	Polyvinylchloride, phthalate esters
58	Rear washer fluid reservoir	Polyethylene
59	Quarter inner trim finishing panel	Propylene-ethylene copolymer

Table A-1-7. Plastics in a 1996 Dodge Caravan and a 1997 Chevrolet Camaro Engine Compartment Parts [8]

Vehicle and Model	Part	Description	Plastic
1996 Dodge Caravan	5235267AB	Battery Cover	PP
	4861057	Resonator Structure	PP
	5303058	Resonator Intake Tube	EPDM Rubber
	4678345	Air Ducts	PE or PP
	4683264	Brake Fluid Reservoir	PP
	4860446	Kick Panel Insulation	PVC
	4857041A	Headlight Clear Lens	PC
	4857041A	Headlight Casing (Black)	POM
	4716345B	Fender Sound Reduction foam	PS
	4716832B	Hood Liner Face	PET
	4716051	Windshield Wiper Structure	Fiberglass/Polyester/styrene
Chevrolet Camaro 1997	10296526	Front Wheel Well Liner	PP,PE
	10297291	Air Inlet	PP,PE
	10278015	Hood Insulator	Nylon 6/phenolic binder
	52465337	Radiator Inlet/Outlet Tank	Nylon 6,6
	22098787	Engine Cooling Fan	Nylon6
	26019594	Power Steering Fluid Reservoir	Nylon 6,6
	10310333	Windshield Laminate	
	52458965	Blower Motor Housing	PP

APPENDIX A-2

MINI-SCALE TEST DATA FOR PLASTIC PARTS

(References in Chapter I

Table A-2-1. Melting Point, Glass Transition Temperature and Heat of Fusion of a 1996 Dodge Caravan Plastic Parts [1]

Part	Plastic	T_m (°C)	T_{glass} (°C)	ΔH_{fusion} (J/g)
GJ42SK4A	PET	76; 99; 254	-5.6	0.89; 5.32; 2.59
GJ42SK4B	PU	Amorphous		
GJ42SK4C	PU	Amorphous	-11.9	
GJ42SK4D	Nylon 6	221	41.5	57
GJ42SK4E	PET	Amorphous		
JF48SKA	PU	Amorphous	-2.3	
JF48SK5B	PVC	Amorphous		
JF48SKC	PC	Amorphous	-9.1	
PL98SX8A	PC	Amorphous	140.1	
PL98SX8B	PU	Amorphous		
3009	EPDM	Amorphous		
4364944A	PE/PP blend	128; 167	-15.0	19; 64
4364944B	PE/PP blend	129; 166	-15.7	19; 64
4612512A	PP	164		66
4612512B	EPDM	Amorphous		
4612512C	EPDM	Amorphous		
4674711A	PU	Amorphous		
4674711B	PVC	Amorphous		
4675359A	EPDM	Amorphous		
4675359B	EPDM	Amorphous		
4678345A	PE	128		149
4678345B	PP	166		63
4680250A	Natural rubber	Amorphous		
4680250B	Fibers	155		19
4680250C	Polyester	Amorphous	-5.0	
4683264A	PP	164		70
4683264B	PP	165	-13.7	76
4707580	PE	128		166
4707808A		82		15
4707808B		254		39
4707743C	ABS	Amorphous	-11.1	
4716051	SMC	Amorphous		
4716345A	PS	Amorphous		
4716345B	PS	Amorphous		
4716832A	PET/Cell/Epoxy	250		5
4716832B	PET	245		7
4716895	PP	166		60
4716896A	Mixed fibers	232		5
4716896B	PVC	Amorphous		

Table A-2-1 continued on the next page

Table A-2-1 continued from the previous page

Part	Plastic	T_m (^oC)	T_{glass} (^oC)	ΔH_{fusion} (J/g)
4716896C	PVC-Hydrocarbon	174		
4734033	PVC	Amorphous		
4734039A	Nylon 66	259		39
4734039B	TPO	157		31
4734041A	Nylon 66	257	82.0	31
4734041B	TPO	154		15
4734042A	TPR	259	82.4	35
4734042B	TPR	154		18
4734063	PP	124; 162	52.6	0.59; 49
4734067A	ABS/PVC	Amorphous		
4734067B	EVA	Amorphous	39.0	
4734071	PP	Amorphous		
4734072	PP	Amorphous		
4734073	PP	Amorphous		
4734074	PP	165		57
4734080	PP	Amorphous		
4734081	PP	Amorphous		
4734225	PP	164	2.0	59
4734367	PP	163		50
4734370	ABS /PVC	Amorphous		
4734724	TPO	Amorphous		
4883140A	PE	128		161
4883140B	Nylon 12	171		49
4883140C	PE	Amorphous		
4857041A	PC	Amorphous		
4857041B	PC	Amorphous	144.0	
4857041C	POM	174		161
4857041D	Polyimide	Amorphous	207.0	
4857041E	PC	Amorphous	144.0	
5235267	PP	164	-7.0	54

Table A-2-2. Melting Point, Glass Transition Temperature and Heat of Fusion of a 1997 Chevrolet Camaro Plastic Parts [4]

Part	Plastic	T_m (°C)	T_{glass} °C	ΔH_{fusion} (J/g)
10138735	PE	124	-53	125
10153750	PP	161		90
10208798	Hydrocarbon	Amorphous	13	
10231299	PU	Amorphous	117	
10243962	PP/PE copolymer	122, 145		21, 58
10246204A			-50	
10246204B	PP/PE copolymer	119, 156	24	20, 71
10269100A	PS	Amorphous	123	
10269100B			108	
10269100C	ABS	Amorphous	78	
10269102A	PC	108		147
10269102B			42	
10269102C		109		158
10277446A	PP	124, 161		7, 91
10277446B			-30	
10277466		112, 155	66	6, 73
10277772A	Nylon 6	220	38	122
10277772B	PU	Amorphous	129	
10277772C	Phenolic	Amorphous	20	
10278015A		206	5	8
10278015B				
10278989A	Nylon 6	220		60
10278989B	PP	160		24
10282257A	PE	107	69	87
10282257B	PU	Amorphous		
10284967		273, 288	80	48, 71
10296526	PP/PE copolymer	164	123	133
16215781A	ABS	Amorphous	107	
16215781B	PS/phenolic	Amorphous	106	
16215781C	SA	Amorphous	111	
16514312	PE	47, 99		22, 107
16524838	PP/PE Copolymer	118, 162		6, 64
16633455	PP/PE copolymer	124, 161		13, 94
16795366			110	
16795385A	PP	159	0	60
16795385B	PET		108	
16795385C	PET			

Table A-2-2 continued on the next page

Table A-2-2 continued from the previous page

Part	Plastic	T_m (°C)	T_{glass} ^oC	ΔH_{fusion} (J/g)
22098787	Nylon 6/6	219	30	73
26024352	Nylon 6/6	261	35	83
52458712		159		86
52458713	PP	162		74
52458898	PP	160		71
52458938	PU	Amorphous	14, 46	
52458941	PU	Amorphous	40	
52458960	PU	164	13	86
52458961A	PU	Amorphous	2, 42	
52458961B	PU	97		14
52458965	PU	159		66
52458972	PU	Amorphous	31	
52458976	PU	Amorphous	76, 130	
52461468A	Nylon	258		50
52461468B		162		102
52461468C	Hydrocarbon	114, 149	-22	1, 14
52461468D	EPDM & PS	119, 151	-22	12, 20
52464968			65	
52465340	Nylon 6/6	261	102	118
52472378	PU	Amorphous	4	

Table A-2-3. Melting Point, Glass Transition Temperature and Heats of Fusion and Reaction of a 1996 Dodge Caravan and a 1997 Chevrolet Camaro Plastic Parts [8]

Part	**Description**	**Plastic**	**Endothermic 1**		**Endothermic 2**		**Exothermic**	
			T_m (^oC)	**ΔH_{fusion} (J/g)**	**T_m (^oC)**	**ΔH_{fusion} (J/g)**	**Exotherm (^oC)**	**$\Delta H_{reaction}$ (J/g)**
1996 Dodge Caravan								
5235267AB	Battery Cover	PP	128	236				
4861057	Resonator Structure	PP	167	88				
5303058	Resonator Intake Tube	EPDM Rubber	161	61			68	2.74
4683264	Brake Fluid Reservoir	PP	168	138				
4857041A	Headlight Clear Lens	PC	143					
4857041A	Headlight Casing (Black)	POM	143					
4716051	Windshield Wiper Structure	Fiberglass/Polyester/styrene	77	61			50	12
1997 Chevrolet Camaro								
10296526	Front Wheel Well Liner	PP,PE	168	88			240	7
10297291	Air Inlet	PP,PE	113	11	168	65	234	7
52465337	Radiator Inlet/Outlet Tank	Nylon 6,6	265	59				
22098787	Engine Cooling Fan	Nylon6	60	1.28	221	54		
26019594	Power Steering Fluid Reservoir	Nylon 6,6	265	56				
52458965	Blower Motor Housing	PP	167	101			249	

Table A-2-4. Melting Point, Glass Transition Temperature and Heat of Fusion of Possible Replacements Plastics for Vehicle Parts [3]

Plastic	**T_m (^{o}C)**	**T_{glass}(^{o}C)**	**ΔH_{fusion} (J/g)**
Polypropylene, pro-fax SB 786	122;160;164	-3	36; 92
Polypropylene, pro-fax 8523	118;166	2	8; 68
Polypropylene, 151 (FR)	128;160	(-8,72)	14; 58
Polypropylene, 156 FR	124;166	(-4,74)	7; 50
Nylon 66, Ultramid A3K	262	64	113
Nylon 66, Ultramid A3X2G5 (FR)	262	52	86
Nylon 66, 200H (FR)	260	46	73
Nylon 66, 299X	260	58	79
Nylon 6, standard	219	59	129
Nylon 6, nano-composite	216	(-1,56)	103

Table A-2-5. Vaporization or Decomposition Temperature ($T_{v\ or\ d}$) and Rates for a 1996 Dodge Caravan Plastic Parts [1]

Part	Plastic	Nitrogen						Air					
		Initial		Major		Secondary		Initial		Major		Secondary	
		$T_{v\ or\ d}$ (^{o}C)	Rate (%/^{o}C)	$T_{v\ or\ d}$ (^{o}C)	Rate (%/^{o}C)	$T_{v\ or\ d}$ (^{o}C)	Rate (%/^{o}C)	$T_{v\ or\ d}$ (^{o}C)	Rate (%/^{o}C)	$T_{v\ or\ d}$ (^{o}C)	Rate (%/^{o}C)	$T_{v\ or\ d}$ (^{o}C)	Rate (%/^{o}C)
GJ42SK4A	PET	298	0.02	442	0.78	329	0.34			305	0.40	337	0.33
GJ42SK4B	PU			286	1.50	382	0.71			279	2.06	505	1.55
GJ42SK4C	PU	267	1.28	344	4.37	447	0.91	264	0.86	363	1.11	442	0.33
GJ42SK4D	Nylon 6	276	0.22	401	2.55	358	0.87	276	0.20	380	1.26	358	1.06
GJ42SK4E	PET									248	4.36	510	0.72
JF48SK5A	PU	250	0.25	346	0.99	286	0.45			269	3.83	430	0.56
JF48SK5B	PVC			269	2.47	284	1.96			397	3.07	531	1.21
JF48SK5C	PC			413	10.07	447	0.76						
PL98SX8A	PC	399	0.48	440	5.70			404	0.38	454	7.28	548	1.90
PL98SX8B	PU	267	0.23	344	2.44					252	2.62	291	0.44
3009	EPDM			375	0.20	435	1.50	334	0.32	565	4.96	435	1.29
4364944A	PE/PP			411	13.38					284	11.20		
4364944B	PE/PP			409	10.40					305	5.20	433	0.23
4612512A	PP			429	10.26					296	2.13	325	1.68
4612512B	EPDM	404	0.29	450	1.50			317	0.21	447	1.89	543	3.94
4612512C	EPDM	399	0.24	452	1.51			349	0.29	572	3.73	452	1.50
4674711A	PU	224	0.27	269	1.48	293	1.40			262	4.06		
4674711B	PVC			255	2.52	461	0.01			257	2.83	363	0.33
4675359A	EPDM			305	0.33	438	2.70			276	1.50	416	0.27
4675359B	EPDM	310	0.20	454	2.00	721	0.25			334	0.62	416	0.27
4678345A	PE			438	8.80			293	0.40	404	11	375	2.05
4678345B	PP			430	13.80			303	0.66	341	2.22	375	2.05

Table A-2-5 continued on the next page

Table A-2-5 continuing from the previous page

Part	Plastic	Nitrogen						Air					
		Initial		Major		Secondary		Initial		Major		Secondary	
		$T_{v\ or\ d}$ (°C)	Rate (%/°C)	$T_{v\ or\ d}$ (°C)	Rate (%/°C)	$T_{v\ or\ d}$ (°C)	Rate (%/°C)	$T_{v\ or\ d}$ (°C)	Rate (%/°C)	$T_{v\ or\ d}$ (°C)	Rate (%/°C)	$T_{v\ or\ d}$ (°C)	Rate (%/°C)
4680250A	Rubber	368	0.56	428	1.44			267	0.15	418	1.24	495	1.61
4680250B	Fibers			332	1.57	406	0.39			305	1.77	397	0.59
4680250C	Polyester	296	0.32	416	5.25	704	0.61	276	0.54	339	1.98	406	0.12
4683264A	PP			413	14.90					308	16.79		
4683264B	PP			416	15.10					293	12.30		
4707580	PE			442	12.70			267	0.98	356	3.06	406	1.25
4707808A		291	0.70	363	2.82			310	0.30	445	2.59		
4707808B				382	9.08	462	0.45			399	11.20		
4707743C	ABS			365	8.17					373	9.03		
4716051	SMC	382	0.49	382	0.49	700	0.86			341	0.48	723	0.17
4716345A	PS	233	0.25	394	0.49	425	0.45	233	0.21	339	0.54	266	0.21
4716345B	PS	281	0.17	401	0.49	502	0.06	257	0.17	432	0.21	288	0.21
4716832A	PET etc	60	0.04	322	1.30	397	0.19			300	2.28	397	0.78
4716832B	PET	67	0.03	325	1.33	397	0.20	310	2.53	394	5.54	370	0.63
4716895	PP			429	15.12					310	1.82	368	1.04
4716896A	Fibers	55	0.06	288	0.97	380	0.53	48	0.07	288	1.09	339	0.41
4716896B	PVC			274	1.15	459	0.08			261	0.82	391	0.26
4716896C	PVC-Hydro	267	1.01	726	1.34	565	0.05			267	0.30	387	0.35
4734025		293	0.63	308	1.64	358	0.83	267	1.23	293	2.98	365	0.65
4734033	PVC			437	6.95					267	2.91	440	0.20
4734039A	Nylon 66			418	4.70	447	0.40			421	5.89	514	0.53
4734039B	TPO	291	0.40	433	5.60			284	0.81	396	0.70	391	0.70
4734041A	Nylon 66			428	3.60	457	0.30			428	3.29	526	0.34
4734041B	TPO	308	0.50	440	3.80					284	0.78	406	4.74
4734042A				428	3.30					425	2.75	500	0.46

Table A-2-5 continued on the next page

Table A-2-5 continued from the previous page

Part	Plastic	Nitrogen						Air					
		Initial		Major		Secondary		Initial		Major		Secondary	
		$T_{v\ or\ d}$ (^oC)	Rate (%/^oC)	$T_{v\ or\ d}$ (^oC)	Rate (%/^oC)	$T_{v\ or\ d}$ (^oC)	Rate (%/^oC)	$T_{v\ or\ d}$ (^oC)	Rate (%/^oC)	$T_{v\ or\ d}$ (^oC)	Rate (%/^oC)	$T_{v\ or\ d}$ (^oC)	Rate (%/^oC)
4734042B		303	0.50	440	4.30					284	0.59	406	4.16
4734063	PP			437	6.95			288	0.74	325	3.98		
4734067A	ABS/PVC			233	0.50	245	1.40			240	1.19	435	0.30
4734067B		361	0.10	462	1.10	776	0.10	361	0.20	466	0.65	433	0.16
4734074	PP			373	2.00	401	0.90			298	0.71	334	3.14
4734225	PP			428	5.10					274	1.05	298	5.72
4734367	PP			447	7.5			288	0.70	339	3.29		
4734370	ABS /PVC			226	0.47	248	1.3	228	0.55	238	1.43	430	0.30
4734396		226	0.47	428	0.44								
4734724	TPO	349	0.32	430	4.69			286	0.57	334	0.56	372	1.25
4883140A	PE			440	16.79			291	1.09	387	5.88	438	4.31
4883140B	Nylon 12	214	0.20	416	10.47			224	0.11	418	8.99	382	0.38
4883140C	PE	394	0.40	430	3.98			291	1.58	382	4.90	418	2.08
4857041A	PC			445	3.60					411	7.49	514	1.24
4857041B	PC			476	7.47					450	4.59	517	1.04
4857041C	POM			310	3.26					252	17.02		
4857041D	Polyimide			522	2.52			517	2.52	558	7.67		
4857041E	PC			454	4.74					413	7.10	522	1.21
5235267	PP			423	16.79					346	2.03	384	1.16

Table A-2-6. Vaporization or Decomposition Temperatures ($T_{v\ or\ d}$) and Rates for a 1997 Chevrolet Camaro Plastic Parts [4]

Part	Plastic	Nitrogen						Air					
		Initial		Major		Secondary		Initial		Major		Secondary	
		$T_{v\ or\ d}$ (°C)	Rate (%/°C)	$T_{v\ or\ d}$ (°C)	Rate (%/°C)	$T_{v\ or\ d}$ (°C)	Rate (%/°C)	$T_{v\ or\ d}$ (°C)	Rate (%/°C)	$T_{v\ or\ d}$ (°C)	Rate (%/°C)	$T_{v\ or\ d}$ (°C)	Rate (%/°C)
10138735	PE	403	2.73	403	2.73	425	1.42	280	0.56	407	2.49	443	1.09
10153750	PP	354	2.56	354	2.56	378	1.32	284	0.48	347	2.30	691	0.04
10208798	Hydrocarbon	295	0.31	459	1.76			291	0.30	564	4.32	602	0.30
10231299	PU	266	0.28	363	2.12	309	0.32	240	0.04	311	0.66	528	0.04
10243962	PP/PE	374	1.63	374	1.63	385	1.53	300	1.26	300	1.26	523	0.19
10246204A		266	0.70	351	5.86			265	2.62	265	2.62	299	0.99
10246204B	PP/PE	389	3.82	389	3.82	443	0.21	352	5.32	352	5.32	369	1.22
10269100A	PS	371	10.58	371	10.58			351	8.08	351	8.08	544	0.12
10269100B		338	0.97	365	2.02	485	0.09	273	3.87	273	3.87	519	0.57
10269100C	ABS	269	4.16	269	4.16	432	0.86	376	0.32	376	0.32	608	0.26
10269102A	PC	465	5.86	465	5.86			271	0.11	356	2.23	432	1.32
10269102B		271	1.01	333	2.39			253	3.72	253	3.72	275	0.84
10269102C		287	0.04	434	9.77			276	0.24	379	5.45	432	1.14
10277446A	PP	403	1.90	403	1.90	548	0.04	342	3.67	342	3.67	582	0.08
10277446B		262	0.81	329	1.97			266	1.50	313	2.67		
10277466		369	0.18	416	2.94	557	0.04	369	0.18	416	2.94	557	0.04
10277772A	Nylon 6	284	0.08	401	5.26	358	0.40	405	1.81	494	1.94	396	1.82
10277772B	PU	264	1.48	264	1.48	333	1.13	253	3.26	253	3.26	530	0.15
10277772C	Phenolic	70	0.01	322	0.03	591	0.03	260	0.02	470	0.15	320	0.04
10278015A		320	0.70	369	1.50	445	0.14	302	1.27	302	1.27	488	0.46
10278015B		345	0.02	492	0.04	611	0.03	488	0.15	526	0.36		
10278989A	Nylon 6	331	0.21	389	2.44	687	0.15	385	1.50	405	3.43	483	0.81
10278989B	PP	325	0.29	434	3.07	349	0.74	313	5.11	313	5.11	463	0.23
10282257A	PE	436	6.55	436	6.55	781	0.11	385	1.36	445	3.50		

Table A-2-6 continued on the next page

Table A-2-6 continued from the previous page

Part	Plastic	Nitrogen						Air					
		Initial		Major		Secondary		Initial		Major		Secondary	
		$T_{v\ or\ d}$ (^{o}C)	Rate (%/^{o}C)	$T_{v\ or\ d}$ (^{o}C)	Rate (%/^{o}C)	$T_{v\ or\ d}$ (^{o}C)	Rate (%/^{o}C)	$T_{v\ or\ d}$ (^{o}C)	Rate (%/^{o}C)	$T_{v\ or\ d}$ (^{o}C)	Rate (%/^{o}C)	$T_{v\ or\ d}$ (^{o}C)	Rate (%/^{o}C)
10282257B	PU	202	0.16	266	1.21	336	0.81	204	0.18	255	4.05	302	0.67
10284967		289	0.52	342	0.79	367	0.71	271	0.53	316	2.70	526	0.37
10296526	PP/PE	434	15.77	434	15.77			282	8.19	282	8.19		
16215781A	ABS	401	10.35	401	10.35	430	0.51	374	5.21	374	5.21	532	1.09
16215781B	PS/phenolic	407	9.92	407	9.92	477	0.20	398	3.60	485	3.53		
16215781C	SA	345	5.43	345	5.43	414	0.13	300	14.85	300	14.85	349	0.27
16514312	PE	360	0.23	405	5.58	421	1.99	356	0.36	427	3.14	494	0.28
16524838	PP/PE	369	3.69	369	3.69			336	1.63	336	1.63	490	0.02
16633455	PP/PE	416	2.65	416	2.65			331	2.27	331	2.27	354	2.04
16795366		255	0.60	342	2.63			262	3.35	262	3.35	544	0.35
16795385A	PP	365	2.91	365	3.91	709	0.13	284	3.03	284	3.03	687	0.18
16795385B	PET	342	2.15	342	2.15	398	1.23	345	2.20	345	2.20	526	0.66
16795385C	PET	271	0.90	325	1.93	271	0.90	253	3.61	253	3.61	273	1.04
22098787	Nylon 6/6	423	4.40	423	4.40			430	3.90	430	3.90	479	0.42
26024352	Nylon 6/6	421	3.20	421	3.20			425	2.64	425	2.64	535	0.15
52458712		447	10.23	447	10.23			298	0.25	351	3.17		
52458713	PP	378	1.36	412	1.56			295	0.42	345	2.66		
52458898	PP	376	1.70	376	1.70	405	1.68	291	0.51	345	2.79		
52458938	PU	264	0.11	702	0.48	452	0.30	255	0.14	503	0.39	684	0.29
52458941	PU	266	0.12	447	0.57	691	0.22	251	0.12	459	0.42	709	0.27
52458960	PU	436	7.35	436	7.35			356	1.36	375	3.20		
52458961A	PU	262	0.14	325	0.43	613	0.04	269	0.18	483	1.56	615	0.07
52458961B	PU	251	0.13	459	1.21	291	0.16	273	0.45	452	0.44	501	0.32
52458965	PU	396	1.40	432	2.74			295	0.47	347	2.95	333	1.10
52458972	PU	291	0.14	434	0.55	698	0.26	246	0.15	447	0.41	696	0.35
52458976	PU	347	1.00	347	1.00	501	0.14	340	0.62	483	0.63	709	0.04

Table A-2-6 continued on the next page

Table A-2-6 continued from the previous page

Part	Plastic	Nitrogen						Air					
		Initial		Major		Secondary		Initial		Major		Secondary	
		$T_{v\ or\ d}$ (^oC)	Rate (%/^oC)	$T_{v\ or\ d}$ (^oC)	Rate (%/^oC)	$T_{v\ or\ d}$ (^oC)	Rate (%/^oC)	$T_{v\ or\ d}$ (^oC)	Rate (%/^oC)	$T_{v\ or\ d}$ (^oC)	Rate (%/^oC)	$T_{v\ or\ d}$ (^oC)	Rate (%/^oC)
52461468A	Nylon	418	3.12	418	3.12			430	4.07	430	4.07	517	0.33
52461468B		445	13.07	445	13.07			293	0.68	342	2.81	335	1.86
52461468C	Hydrocarbon		0.41	432	2.95	705	0.68	313	0.37	351	1.05	711	0.86
52461468D	EPDM/PS	318	0.54	416	2.10			282	1.64	282	1.64	459	0.83
52464968		253	0.74	356	1.45	311	0.63	251	0.81	289	3.41		
52465340	Nylon 6/6	407	7.35	407	7.35	452	0.29	430	5.58	430	5.58	463	0.32
52472378	PU	269	0.87	340	3.01			271	1.24	271	1.24	548	0.08

Table A-2-7. Vaporization or Decomposition Temperature ($T_{v\ or\ d}$) and Rates in Nitrogen for Replacement Plastics for Vehicle Parts [3]

Plastic	**Initial Weight loss**			**Major weight loss**			**Secondary weight loss**			**Residue%**
	$T_{v\ or\ d}$ °C	**wt loss %**	**Rate %/°C**	**$T_{v\ or\ d}$ °C**	**wt loss %**	**Rate %/°C**	**$T_{v\ or\ d}$ °C**	**wt loss %**	**Rate %/°C**	
Polypropylene										
Profax SB 786	426	99.92	9.98	426	99.92	9.98				0.07
Profax 8523	429	99.91	13.13	429	99.91	13.13				0.06
151 (FR)	238	8.83	0.35	434	78.61	4.84				7.61
156 (FR)	328	54.69	5.49	328	54.69	5.49	398	24.81	0.58	3.76
Nylon 66										
Ultramid A3K	409	16.90	0.95	427	58.06	3.69	585	18.03	0.18	6.69
Ultramid A3X2G5 (FR)	383	44.60	1.10	383	44.60	1.10	450	25.44	0.58	33.65
66, 200H (FR)	374	63.25	10.16	374	63.25	10.16	468	20.16	0.94	4.79
66, 299X	338	15.27	0.86	413	71.64	1.47	585	12.46	0.16	0.42
Nylon 6										
Standard	417	98.70	6.41	417	98.70	6.41				0.53
With nano composite	398	20.05	1.71	419	70.80	3.69				6.25

Table A-2-8. Vaporization or Decomposition Temperature ($T_{v\ or\ d}$) and Rates in Air for Replacement Plastics for Vehicle Parts [3]

Plastic	Initial Weight loss			Major weight loss			Secondary weight loss			Residue%
	$T_{v\ or\ d}$ °C	wt loss %	Rate %/°C	T_v/T_d °C	wt loss %	Rate %/°C	T_v/T_d °C	wt loss %	Rate %/°C	
Polypropylene										
Profax SB 786	309	84.85	6.56	309	84.85	6.56				0.00
Profax 8523	312	89.72	11.41	312	89.72	11.41	429	5.83	0.21	0.26
151 (FR)	242	5.60	0.31	335	18.64	0.92	347	13.83	0.97	2.21
156 (FR)	328	42.42	3.65	328	42.42	3.65	517	10.61	0.19	2.89
Nylon 66										
Ultramid A3K	403	15.54	0.75	424	58.93	4.61	526	19.68	0.40	0.00
Ultramid A3X2G5 (FR)	370	2.77	0.16	417	30.11	1.53	461	9.98	0.28	31.18
66, 200H (FR)	368	52.90	8.80	368	52.90	8.80	534	24.62	1.98	0.28
66, 299X	327	13.65	0.78	431	40.91	2.26	421	21.35	2.49	0.24
Nylon 6										
Standard	403	29.01	3.07	415	53.28	2.35	578	12.19	0.14	0.10
With nano composite	411	90.66	4.88	411	90.66	4.88				3.58

Table A-2-9. Density, Thermal Conductivity, and Heat Capacity of a 1996 Dodge Caravan Plastic Parts [1]

Part	Plastic	ρ g/cm^3	k W/m-^{o}C	Heat Capacity (J/g-K)									
		Temperature (^{o}C)											
		20	20	-50	-40	-20	0	20	40	60	80	100	200
GJ42SK4A	PET	0.69	0.04	0.863	0.866	0.932	1.024	1.101	1.194	1.271	1.511	2.287	1.558
GJ42SK4B	PU	0.10		1.131	1.151	1.216	1.307	1.396	1.492	1.597	1.711	1.846	2.242
GJ42SK4C	PU	0.06		1.194	1.500	1.583	1.638	1.696	1.748	1.810	1.870	2.166	2.162
GJ42SK4D	Nylon 6	1.20	0.11	0.923	0.951	1.071	1.149	1.222	1.306	1.392	1.474	1.578	2.192
JF48SK5A	PU	0.11	0.04	0.963	0.986	1.040	1.117	1.182	1.252	1.314	1.383	1.471	1.768
JF48SK5B	PVC	1.20	0.14	0.829	0.836	0.877	0.933	0.976	1.022	1.068	1.119	1.182	1.374
JF48SK5C	PC	1.12	0.18	0.772	0.776	0.827	0.890	0.953	1.018	1.082	1.144	1.217	1.679
PL98SX8A	PC	1.18	0.27	0.806	0.814	0.871	0.934	0.999	1.074	1.142	1.194	1.247	1.510
PL98SX8B	PU	0.09	0.06	0.973	1.066	1.113	1.156	1.197	1.235	1.272	1.312	1.349	1.556
3009	EPDM	1.21	0.45	0.799	0.886	1.005	1.077	1.109	1.159	1.147	1.198	1.250	1.484
4364944A	PE/PP	0.91	0.17	0.950	0.963	1.040	1.142	1.245	1.346	1.461	1.581	1.759	1.983
4364944B	PE/PP	0.88	0.21	1.005	1.019	1.100	1.202	1.308	1.425	1.552	1.712	1.913	2.147
4612512A	PP	1.06	0.23	0.930	0.958	1.026	1.130	1.233	1.347	1.462	1.577	1.744	2.082
4612512B	EPDM	1.15	0.30	1.153	1.229	1.327	1.353	1.382	1.402	1.449	1.497	1.541	1.745
4612512C	EPDM	1.16	0.36	0.753	0.821	0.927	0.988	1.026	1.030	1.075	1.124	1.173	1.394
4674711A	PU	0.02	0.02	1.062	1.131	1.189	1.244	1.292	1.341	1.383	1.426	1.471	1.653
4674711B	PVC	1.95	0.25	0.697	0.718	0.777	0.824	0.861	0.898	0.942	0.987	1.032	1.141
4675359A	EPDM	0.44	0.07	1.446	1.543	1.601	1.626	1.690	1.768	1.852	1.923	1.990	2.304
4675359B	EPDM	0.41	0.21	0.916	0.973	1.051	1.097	1.137	1.189	1.203	1.251	1.300	1.507
4678345A	PE	0.95	0.31	0.938	0.959	1.044	1.162	1.274	1.397	1.553	1.795	2.200	2.025
4678345B	PP	1.04	0.23	0.935	0.958	1.023	1.104	1.183	1.274	1.379	1.504	1.652	1.934
4680250A	Rubber	1.26	0.24	0.724	0.827	0.940	0.986	1.029	1.084	1.144	1.166	1.204	1.391
4680250B	Fibers	0.22		1.105	1.133	1.215	1.298	1.386	1.475	1.552	1.693	2.036	2.102

Table A-2-9 continued on the next page

Table A-2-9 continuing from the previous page

Part	Plastic	ρ g/cm^3	k W/m-^{o}C	Heat Capacity (J/g-K)									
		Temperature (^{o}C)											
		20	20	-50	-40	-20	0	20	40	60	80	100	200
4680250C	Polyester	1.15	<0.01	0.985	1.032	1.120	1.157	1.207	1.262	1.366	1.435	1.521	1.785
4683264A	PP	0.90	0.19	1.041	1.068	1.152	1.264	1.382	1.501	1.629	1.773	2.033	2.247
4683264B	PP	0.90	0.21	1.230	1.261	1.337	1.445	1.562	1.687	1.829	1.974	2.174	2.476
4707580	PE	0.95	0.37	1.037	1.044	1.121	1.216	1.330	1.473	1.649	1.882	2.368	2.122
4707808A		1.16		0.974	0.998	1.120	1.221	1.298	1.435	1.783	2.411	1.563	1.752
4707808B		1.10		0.722	0.728	0.765	0.808	0.845	0.882	0.931	0.982	1.043	1.315
4707743C	ABS	1.07	0.21	0.858	0.892	0.946	0.999	1.057	1.122	1.182	1.239	1.303	1.733
4716051	SMC	1.64	0.37	0.605	0.620	0.653	0.689	0.726	0.767	0.813	0.858	0.906	1.140
4716345A	PS	0.90	0.17	1.021	1.063	1.118	1.173	1.234	1.300	1.378	1.434	1.487	1.700
4716345B	PS	1.30	0.10	0.955	0.984	1.043	1.098	1.159	1.231	1.310	1.362	1.412	1.624
4716832A	PET etc	0.09	0.04	0.825	0.844	0.906	0.973	1.043	1.118	1.184	1.230	1.291	1.664
4716832B	PET	0.66	0.09	0.581	0.595	0.642	0.695	0.749	0.808	0.875	0.926	0.986	1.319
4716895	PP	0.93	0.23	1.111	1.164	1.242	1.310	1.392	1.492	1.613	1.743	1.925	2.200
4716896A	Fibers	1.60		0.761	0.770	0.839	0.896	0.953	1.015	1.021	1.115	1.151	1.400
4716896B	PVC	1.00	0.23	0.634	0.651	0.690	0.724	0.753	0.785	0.821	0.855	0.888	1.052
4716896C	PVC-Hyd	1.60	0.10	0.762	0.795	0.851	0.896	0.932	0.973	1.016	1.058	1.098	1.239
4734025		0.11	<0.01	0.762	0.790	0.834	0.885	0.932	0.981	1.029	1.070	1.115	1.334
4734033	PVC	1.38		0.779	0.808	0.895	0.956	1.010	1.062	1.128	1.191	1.242	1.412
4734039A	Nylon 66	1.46		0.889	0.915	0.975	1.038	1.110	1.213	1.318	1.450	1.493	1.813
4734039B	TPO	0.93	0.09	1.110	1.190	1.294	1.344	1.385	1.446	1.526	1.609	1.705	1.961
4734041A	Nylon 66	1.50	0.58	0.793	0.813	0.867	0.923	0.990	1.096	1.196	1.286	1.314	1.691
4734041B	TPO	0.97	0.13	1.205	1.246	1.334	1.358	1.408	1.457	1.520	1.592	1.658	1.865
4734042A		1.50	0.40	0.875	0.899	0.956	1.016	1.086	1.199	1.317	1.426	1.461	1.910
4734042B	TPO	0.98	0.05	1.222	1.265	1.369	1.398	1.441	1.478	1.541	1.614	1.690	1.933
4734063	PP	1.19	0.39	1.470	1.053	1.114	1.182	1.263	1.352	1.456	1.537	1.650	1.895
4734067A	ABS/PVC	0.10	0.02	0.718	0.726	0.869	0.957	0.999	1.044	1.092	1.134	1.188	1.345

Table A-2-9 continued on the next page

Table A-2-9 continued from the previous page

Part	Plastic	ρ g/cm³	k W/m-°C	Heat Capacity (J/g-K)									
		Temperature (°C)											
		20	20	-50	-40	-20	0	20	40	60	80	100	200
4734067B		2.10		0.607	0.629	0.726	0.792	0.822	0.920	1.019	0.925	0.915	1.025
4734074	PP	1.21	0.39	0.905	0.910	0.969	1.039	1.112	1.199	1.285	1.377	1.490	1.760
4734225	PP	1.11	0.34	1.128	1.149	1.203	1.291	1.373	1.456	1.553	1.672	1.815	1.947
4734367	PP	1.20	0.33	0.164	1.167	1.223	1.301	1.386	1.474	1.581	1.686	1.817	2.015
4734370	ABS/PVC	0.07	0.15										
4734396		0.12	0.03										
4734650		0.11	0.03										
4734651		0.17	0.04										
4734724	TPO	0.97	0.33	1.062	1.092	1.185	1.224	1.260	1.328	1.413	1.497	1.599	1.872
4883140A	PE	0.94	0.30	1.082	1.083	1.152	1.223	1.353	1.473	1.631	1.817	2.217	2.147
4883140B	Nylon 12	1.04	0.18	0.834	0.867	0.973	1.106	1.211	1.310	1.410	1.498	1.595	1.787
4883140C	ABC/PVC	0.95											
4857041A	PC	1.19	0.20	1.068	1.076	1.142	1.210	1.282	1.357	1.434	1.559	1.658	2.061
4857041B	PC	1.20	0.22	1.300	1.301	1.362	1.427	1.499	1.566	1.623	1.698	1.774	2.177
4857041C	POM	1.41	0.27	1.092	1.118	1.167	1.224	1.285	1.349	1.425	1.528	1.659	1.918
4857041D	Polyimide	1.59		0.560	0.581	0.618	0.659	0.700	0.743	0.788	0.831	0.872	1.050
4857041E	PC	1.18	0.19	0.959	0.959	1.015	1.080	1.156	1.228	1.297	1.373	1.445	1.095
5235267	PP	0.90		1.037	1.074	1.158	1.265	1.369	1.480	1.609	1.776	2.189	2.216

Table A-2-10. Density, Thermal Conductivity, and Heat Capacity of a 1997 Chevrolet Camaro Plastic Parts [4]

Part	Plastic	ρ g/cm^3	k W/m-^{o}C	Heat Capacity (J/g-K)								
		Temperature (^{o}C)										
		20	20	-40	-20	0	20	40	60	80	100	200
10138735	PE	0.80	0.23	1.325	1.412	1.527	1.664	1.827	2.053	2.379	3.027	2.463
10153750	PP	1.04	0.19	1.454	1.539	1.650	1.757	1.867	2.030	2.198	2.388	2.614
10208798	Hydrocarbon	1.19	0.13	1.313	1.425	1.543	1.621	1.609	1.660	1.720	1.777	2.051
10231299	PU	1.04	0.14	1.295	1.371	1.442	1.513	1.576	1.642	1.749	1.991	0.219
10243962	PP/PE	0.88	0.33	1.559	1.660	1.777	1.870	2.013	2.216	2.439	2.795	2.693
10246204A		1.14		2.046	2.261	2.300	2.340	2.400	2.460	2.520	2.620	2.850
10246204B	PP/PE	0.89	0.24	1.563	1.660	1.780	1.880	2.020	2.250	2.450	2.750	2.820
10269100A	PS	0.96	0.26	0.890	0.942	1.009	1.066	1.128	1.197	1.264	1.329	1.706
10269100B		1.21	0.08	1.503	1.581	1.662	1.734	1.809	1.891	1.965	2.032	2.300
10269100C	ABS	0.89	0.10	1.058	1.154	1.261	1.362	1.462	1.560	1.665	1.750	1.938
10269102A	PC	1.18	0.34	1.430	1.568	1.751	1.885	2.120	2.481	2.891	5.303	2.404
10269102B				1.457	1.552	1.585	1.625	1.676	1.722	1.776	1.833	2.101
10269102C				0.856	0.996	1.150	1.290	1.513	1.855	2.662	4.855	1.854
10277446A	PP	1.05	0.19	0.312	0.353	0.432	0.512	0.593	0.705	0.843	1.024	1.164
10277446B			0.13	0.147	0.323	0.408	0.456	0.478	0.496	0.522	0.552	0.702
10277466		1.07	0.36	1.268	1.360	1.480	1.590	1.752	1.800	1.950	2.033	2.310
10277772A	Nylon 6	0.09	0.12	1.303	1.383	1.496	1.600	1.727	1.860	1.963	2.080	3.049
10277772B	PU		0.08	1.620	1.701	1.771	1.822	1.876	1.962	1.981	2.054	2.353
10277772C	Phenolic	0.16	0.28	1.060	1.087	1.127	1.164	1.206	1.247	1.238	1.311	1.420
10278015A		0.06	0.07	1.116	1.144	1.210	1.300	1.370	1.446	1.512	1.586	2.244
10278015B		0.08	0.19	0.921	0.954	0.988	1.017	1.054	1.085	1.118	1.143	1.231

Table A-2-10 continued on the next page

Table A-2-10 continued from the previous page

Part	**Plastic**	**ρ g/cm^3**	**k W/m-^{o}C**	**Heat Capacity (J/g-K)**								
		Temperature (^{o}C)										
		20	**20**	**-40**	**-20**	**0**	**20**	**40**	**60**	**80**	**100**	**200**
10278989A	Nylon 6	0.27	0.11	0.979	1.031	1.101	1.185	1.267	1.344	1.408	1.500	2.133
10278989B	PP	1.14	0.33	0.869	0.923	1.003	1.078	1.150	1.231	1.315	1.402	1.663
10282257A	PE	1.20	0.35	1.270	1.380	1.497	1.578	1.734	2.066	2.481	4.016	2.048
10282257B	PU			2.063	2.131	2.193	2.238	2.292	2.351	2.403	2.445	2.706
10284967		1.20	0.35									
10296526	PP/PE	0.88	0.24	1.434	1.545	1.654	1.756	1.893	2.072	2.266	2.528	2.703
16215781A	ABS	1.43	0.13	1.288	1.346	1.419	1.482	1.558	1.663	1.771	1.931	2.415
16215781B	PS/phenolic	1.36	0.12	1.122	1.191	1.271	1.329	1.392	1.471	1.551	1.646	2.054
16215781C	SA	1.11	0.09	1.076	1.131	1.199	1.255	1.319	1.393	1.481	1.619	2.014
16514312	PE	0.99	0.29	1.535	1.747	1.951	2.098	2.434	3.031	4.046	7.921	2.665
16524838	PP/PE	1.11	0.28	1.363	1.426	1.502	1.583	1.683	1.782	1.893	2.028	2.177
16633455	PP/PE	0.95	0.20	1.504	1.594	1.705	1.796	1.919	2.062	2.223	2.426	2.539
16795366			0.07	1.688	1.759	1.853	1.916	2.002	2.081	2.138	2.204	2.596
16795385A	PP	1.23	0.35	1.175	1.257	1.360	1.445	1.544	1.654	1.786	1.886	2.219
16795385B	PET	1.17	0.31	1.036	1.109	1.165	1.216	1.257	1.336	1.412	1.498	1.965
16795385C	PET			1.444	1.493	1.541	1.596	1.644	1.690	1.737	1.785	2.099
22098787	Nylon 6/6	1.44	0.35	0.902	0.963	1.038	1.121	1.255	1.376	1.483	1.551	2.718
26024352	Nylon 6/6	1.40	0.31	0.996	1.056	1.133	1.212	1.351	1.488	1.585	1.686	2.141
52458712		1.20	0.37	1.294	1.369	1.462	1.553	1.656	1.776	1.902	2.043	2.263
52458713	PP	1.20	0.33	1.091	1.158	1.263	1.365	1.446	1.552	1.667	1.805	1.999
52458898	PP	1.17	0.29	1.042	1.108	1.196	1.278	1.364	1.468	1.582	1.705	1.954
52458938	PU	0.18	0.12	1.176	1.261	1.339	1.416	1.468	1.519	1.564	1.590	1.782
52458941	PU	0.21	0.12	1.344	1.414	1.474	1.533	1.607	1.659	1.721	1.772	1.882
52458960	PU	1.23	0.29	0.930	0.980	1.050	1.150	1.200	1.310	1.410	1.530	1.690
52458961A	PU	0.09	0.17	1.148	1.263	1.304	1.362	1.413	1.446	1.497	1.541	1.638

Table A-2-10 continued on the next page

Table A-2-10 continued from the previous page

Part	Plastic	ρ g/cm^3	k W/m-°C	Heat Capacity (J/g-K)								
		Temperature (°C)										
		20	20	-40	-20	0	20	40	60	80	100	200
52458961B	PU			1.815	1.919	2.031	2.064	2.152	2.239	2.488	2.883	2.515
52458965	PU	1.22	0.39	1.028	1.089	1.178	1.254	1.337	1.434	1.540	1.665	1.857
52458972	PU	0.11	0.19	1.212	1.259	1.340	1.424	1.477	1.478	1.513	1.557	1.712
52458976	PU	1.71	0.17	1.296	1.342	1.403	1.467	1.541	1.612	1.740	1.798	2.021
52461468A	Nylon	1.48	0.41	0.844	0.896	0.964	1.036	1.138	1.255	1.360	1.440	1.912
52461468B		1.07	0.11	1.292	1.361	1.461	1.560	1.667	1.787	1.921	2.092	2.283
52461468C	Hydrocarbon	1.20	0.35	1.562	1.641	1.659	1.663	1.717	1.795	1.889	1.987	2.156
52461468D	EPDM & PS	0.86	0.13	1.714	1.837	1.868	1.878	1.935	2.042	2.186	2.358	2.576
52464968			0.02	1.265	1.366	1.618	1.810	1.908	2.077	2.132	2.422	1.624
52465340	Nylon 6/6	1.18	0.39	1.115	1.170	1.250	1.313	1.437	1.585	1.705	1.812	2.274
52472378	PU			2.062	2.237	2.341	2.395	2.449	2.501	2.561	2.609	2.799

Table A-2-11 Heat Capacity and Thermal Conductivity of Possible Replacements Plastics for Vehicle Parts [3]

Replacement Plastic	c_p (J/g-°C) in Nitrogen											k (W/m-°C) at 30°C in Nitrogen
	Temperature (°C)											
	-50	-40	-20	0	20	40	60	80	100	200	300	
Polypropylene												
Pro-faxSB786	1.010	1.031	1.121	1.233	1.357	1.473	1.600	1.750	1.937	2.155	2.413	0.12
Profax 8523	1.337	1.404	1.501	1.628	1.737	1.894	1.968	2.140	2.382	2.442	2.740	0.12
151(FR)	0.846	0.854	0.879	0.952	1.018	1.084	1.491	1.225	1.307	1.537	1.789	0.17
156(FR)	1.293	1.320	1.416	1.568	1.658	1.760	1.873	2.051	2.157	2.322	2.506	0.16
Nylon 66												
Ultramid A3K	1.446	1.451	1.536	1.651	1.748	1.838	1.997	2.191	2.343	2.652	2.979	0.18
UltramidA3X2G5 (FR)	1.164	1.167	1.229	1.312	1.378	1.441	1.562	1.659	1.754	2.122	2.038	0.21
200H (FR)	1.050	1.071	1.142	1.222	1.303	1.413	1.529	1.571	1.639	2.017	1.991	0.15
299X	1.187	1.225	1.265	1.367	1.461	1.557	1.812	1.895	2.014	2.770	2.736	0.15
Nylon 6												
Standard	1.048	1.081	1.149	1.229	1.317	1.421	1.558	1.732	1.847	3.982	2.487	0.14
With nano composite	1.198	1.188	1.257	1.404	1.547	1.656	1.804	1.953	2.069	4.191	2.729	0.16

APPENDIX A-3

SMALL-SCALE TEST METHODS FOR PLASTIC PARTS

(References in Chapter I)

A-3-1. THE FMVSS 302 TEST FOR FLAMMABILITY OF INTERIOR MATERIALS

The standard specifies burn resistance requirements for materials used in the occupant compartments of motor vehicles [20]. The purpose of the standard is to reduce the deaths and injuries to motor vehicle occupants caused by vehicle fires, especially those originating in the interior of the vehicles from sources such as matches or cigarettes. The standard applies to passenger cars, multipurpose passenger vehicles, trucks, and buses.

Acceptance Criteria

The materials shall not burn nor transmit a flame front across its surface at a rate of more than 102 mm/min (1.7 mm/s). If a material stops burning after 60 seconds of heat exposure and has not burned more than 51-mm from the point where the timing was started, it shall be considered to meet the burn-rate requirement.

Test Conditions

The test is performed in a 381-mm long, 203-mm deep and 356-mm high metal cabinet, shown in Fig. A-3-1 [20]. It has a glass observation window in the front, an opening to permit insertion of the specimen holder and a hole to accommodate tubing for gas burner. For ventilation, it has a 13-mm clearance space around the top of the cabinet, ten hole in the base of the cabinet, each hole 19-mm in diameter and legs to elevate the bottom of the cabinet by 10-mm.

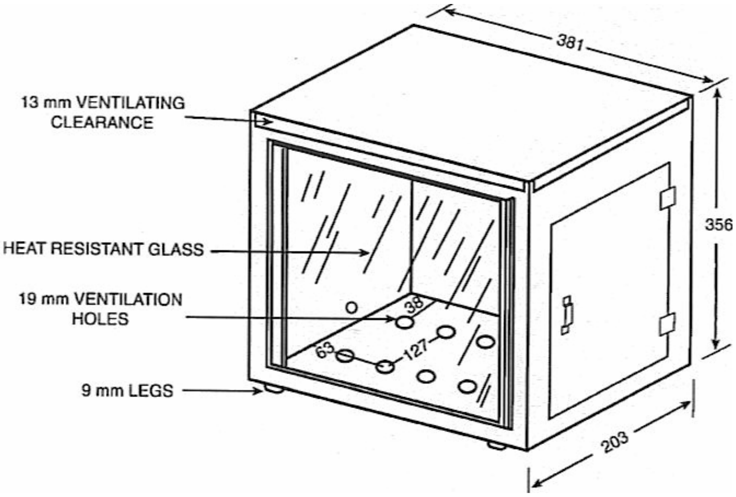


Figure A-3-1. The 571.302 standard test chamber. Figure taken from Ref. 20.

The test specimen is inserted between the two U-shaped frames of metal stock, 25-mm wide and 10-mm high. The interior dimensions of the U-shaped frame are 51-mm wide by 330-mm long. The total width of the frame is 101-mm. A specimen that softens and bends is kept horizontal by supports consisting of 10-mil heat -

resistant wires at 25-mm intervals, inserted over the bottom U-shaped frame. The U-shaped frames hold both sides and one end of the sample even with the open end of the frame.

The ignition source consists of a Bunsen burner with a tube of 10-mm inside diameter. Gas supply is adjusted to provide a vertical, 38-mm high flame. The air inlet to the burner is closed. The gas used in the burner has a flame temperature equivalent to that of natural gas.

Each specimen is rectangular, 102-mm in width and 356-mm in length. The thickness of the specimen is that of the single or composite material used in the vehicle, except that if the thickness exceeds 13-mm, it is cut down to that thickness measured from the surface of the specimen closest to the occupant compartment air space. If the specimens are not flat, they are cut to not more than 13-mm in thickness at any point. The maximum available length or width of a specimen is used where either dimension is less than 356-mm or 102-mm respectively, unless surrogate testing is required. Prior to testing, each specimen is condition for 24 hours at a temperature of 21 ^{o}C and a relative humidity of 50%. The test is conducted under ambient conditions.

The Bunsen burner is placed under the horizontal sample such that the center of the burner tip is 19-mm below the center of the bottom edge of the open end of the sample. The sample is exposed to the flame for 15 seconds. The time for the flame to reach 38-mm from the open end of the sample is noted and used to calculate the burn rate in mm/min.

These procedures were used in the tests following this standard [8].

A-3-2. SMOKE AND TOXICITY TESTS, IMO FTP CODE AND AIRBUS INDUSTRY ABD 0031 (ASTM E662)

Each test uses a smoke chamber consisting of 914 x 610 x 914-mm (36 x 24 x 36-in) enclosure capable of developing and maintaining positive pressure during test periods similar to the ASTM E 662 [8,19]). Both methods subject the sample to a radiant heat flux from a 450 W conical heating element. For the IMO method, the heating element and sample are oriented horizontally; for the Airbus method, they are oriented vertically. A single pilot flame mounted above the specimen is used in the IMO method, while an impinging six-tube pilot burner mounted between the specimen and the heating coil is used in the Airbus method. For the collection of gas samples and for the concentrations measurements of various gases, ASTM E800 (2001) standard test procedure and Nordtest Standard NTFIRE 047 are used.

The samples used in the tests following these standards were 76-mm x 76-mm in dimensions with thickness as received. The ABD 0031 samples were pre-dried at 60 ^{o}C for 24 hours. Samples for both the test methods were conditioned at 23 ^{o}C and 50% relative humidity until constant mass was achieved. Prior to testing, all the samples were covered across the back, along the edges and over the front periphery with a single sheet of aluminum foil. Samples were backed with a sheet of 13-mm (0.5-in) thick piece of non-combustible insulating materials, secured with a spring, and retailing rod.

The IMO and Airbus require that materials meet the limits on the concentrations of toxic gases generated in the standardized tests. The concentration limits are listed in Table A-3-1

Table A-3-1. Toxic Gas Concentration Limits [8]

Toxic Gas	**Concentration (ppm)**	
	Airbus	**IMO**
CO_2	None	None
CO	1000	1450
HF	100	600
HCl	150	600
HBr	None	600
NO_x	100	350
HCN	150	140
SO_2	100	120

A-3-3. GM'S MODIFIED 9833P FLAMMABILITY TEST

In the test, 102-mm (4-in) wide and 298-mm (12-in) long sample inside a U-shaped metal frame, similar to that of FMVSS 571. 302, is exposed on both sides by two radiant heaters (Fig. A-3-2) [15]. The entire sample assembly is kept inside a 1.1-m (44-in) long x 0.51-m (20-in) wide x 1.3-m (50-in) high enclosure with an exhaust fan at the top. In the tests following this standard, each sample was tested at ambient temperature, 93 ^{0}C (200 ^{0}F), 121 ^{0}C (250 ^{0}F) and 149 ^{0}C (300 ^{0}F). Each sample was ignited at the open end by a Meeker type-high temperature burner. Two load cells were used to measure the burning rate and melting rate during fire propagation. Extent of flame spread was also measured. The test was terminated after 300 seconds of burning or if the sample self extinguished. Propylene (PP), fire retarded (FR)-PP, and nylons with and without FR with a sample orientation of 45 ^{0}C were tested.

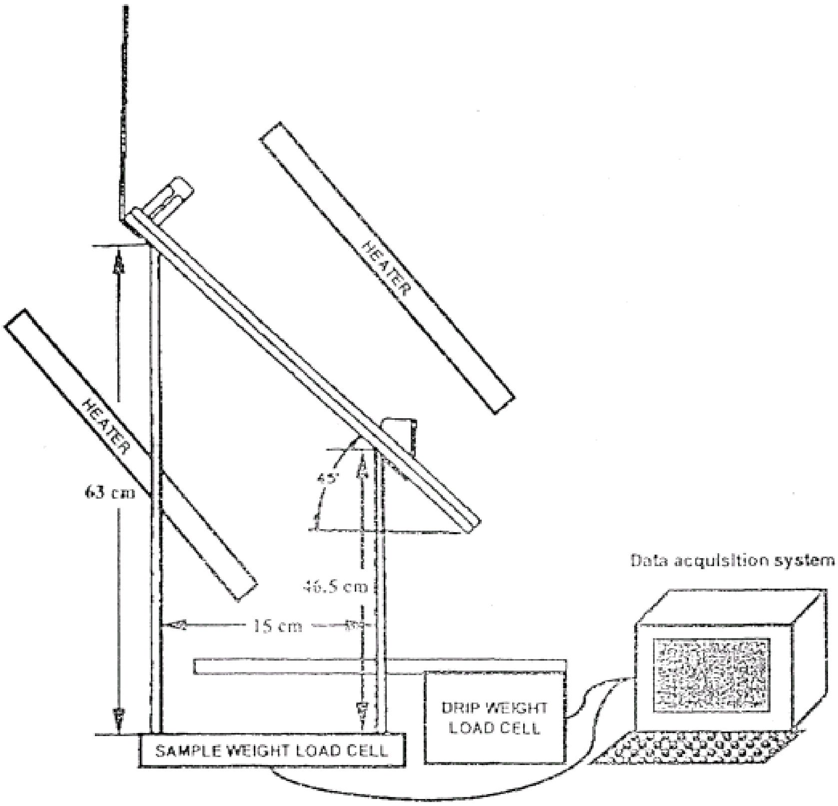


Figure B-3.2 The GM Modified 9833P Flammability Test Apparatus [15].

A-3-4 THE ASTM E1354 STANDARD TEST METHOD USING THE CONE CALORIMETER

The tests were performed following the ASTM E1354 Cone Calorimeter standard test procedure [8, 19]. In the tests, each sample was used in the horizontal orientation with the edge frame and spark igniter. Four types of the tests were performed: full Cone Calorimeter tests, emmisivity tests, ignition tests, and intrinsic heat release tests. The full tests and the intrinsic heat release tests were terminated after flameout and data were recorded as specified in the ASTM E1354. The emmisivity and the ignition tests were terminated two minutes after sustained flaming was observed.

Full Cone Calorimeter tests were generally conducted in duplicate at three heat flux levels: 20, 35, and 50 kW/m^2. A third test was performed if there was a large discrepancy. Up to four additional ignition tests were performed at heat flux levels below 20 kW/m^2. Most samples used were 100-mm x100-mm in dimension with a thickness > 6-mm.

Supplemental toxic gas measurements were also made in the sampling duct of the ASTM E1354 Cone Calorimeter by an FTIR. The ASTM E800 (2001) [19] standard test procedure was used for the collection and concentration measurements of CO, CO_2, HCN, NO_x, and HCl.

A-3-5 THE ASTM E2058 STANDARD TEST METHOD USING THE FIRE PROPAGATION APPARATUS []

The tests were performed following the ASTM E2058 standard test procedure [12,13,14,16,17,19]. For the ignition and combustion tests, each sample was used in a horizontal orientation and for the fire propagation test; each sample was used in a vertical orientation. The horizontal sample was either a square slab (100-mm x 100-mm) or a round slab (100-mm diameter) with thickness > 3-mm.

The sample was placed in a horizontal configuration inside a sample dish made of two layers of 0.05-mm thick aluminum foil. The dish was placed on top of a platform. The sample surface was coated by a fine graphite powder or by a single coat of flat black paint for maximum absorption of the external heat flux applied to the surface of each sample in the test in the presence of a pilot flame. The ignition test was performed under natural airflow (no quartz tube around the sample). The combustion test was performed under forced airflow (quartz tube around the sample).

In the ignition test, performed at various external heat flux values in the range of 10 to 60 kW/m^2, time-to-ignition was measured at each external heat flux value and used to derive the *Critical Heat Flux* (**CHF**) and *Thermal Response Parameter* (**TRP**) values.

In the combustion test, each sample was placed inside the quartz tube and was exposed to 50-kW/m^2 of external heat flux in normal air with a co-airflow rate of 158-mm/s (volumetric flow rate of 2.9 x 10^{-3} m^3/s). In the test, following measurements were made every second until flame extinction or the sample stopped volatilizing:

1) Weight loss;
2) Concentrations of products and oxygen
3) Ambient and hot gas temperatures;
4) Total volumetric (mass) flow rate of product-air mixture through the sampling duct;

5) Optical transmission through the product-air mixture flowing through the sampling duct;
6) Initial and final weight of the sample;
7) Visual observations (flame height and color, smoke particulate shape, size, and color, melting and charring behaviors of the sample).

The measured data were used to calculate the release rates of fuel vapors, heat and products, heat of combustion and product yields.

In the fire propagation test, a 100-mm wide, 300-mm high sample with thickness ≥ 3-mm was used. The sides and back of the sample were covered by a 0.05-mm thick ceramic paper, which was wrapped by two layers of 3-mm thick aluminum foil. The sample was wrapped at five locations by a No. 24-guage nickel/chromium wire (50-mm apart from the ends and from each other). The sample was placed over a ladder type vertical holder. The sample and the holder were wrapped by a 24-guage nickel/chromium wire at about 60-mm. A 100-mm long x 10-mm wide x 10-mm deep dish, made of two layers of 3-mm thick aluminum foil was placed at the bottom of the holder to collect molten mass of the plastic.

The propagation tests were performed under co-airflow rate of 2.9 x 10^{-3} m^3/s (158 mm/s velocity) with an oxygen concentration of 40 %. The bottom 130-mm of the sample was exposed to external heat flux of 50 kW/m^2 in the presence of a pilot flame. The measurements made in the fire propagation test were very similar to those made in the combustion tests. Data measured in the fire propagation and ignition tests were used to calculate the *Fire Propagation Index* (**FPI**).

APPENDIX A-4

SMALL-SCALE TEST DATA FOR PLASTIC PARTS

(References in Chapter I)

1. Data from the Tests Following the FMVSS 571.302 Standard

The tests were performed by SwRI [8]. Plastics from parts from a 1996 Dodge Caravan and a 1997 Chevrolet Camaro, listed in Appendix A in Table A-1-7, were tested by this method. The measured data are listed in Tables A-4-1 and A-4-2.

2. Data for Smoke and Toxicity from the Tests Following the IMO FTP Code and Airbus Industry ABD 0031 Test

The tests were performed by SwRI [8]. Square samples with dimensions of 76-mm x 76-mm and thicknesses as received were exposed to 25 and 50 kW/m^2 of external heat flux in a 914-mm x 610-mm x 914-mm Smoke Chamber. Data were measured for both flaming (F) and non-flaming (NF) fires. Three 1996 Dodge Caravan parts (Appendix A-1, Table A-1-7) were tested. The measured data are listed in Tables A-4-3 to A-4-5.

3. Data for Melting and Flame Spread from the Tests Following the GM Modified 9833P Apparatus

The tests were performed by GM [3, 15]. The test data are listed in Tables A-4-6 to A-4-8.

4. Data from the Tests in the Cone Calorimeter Following the ASTM E1354 Standard Test Procedures

The tests were performed by SwRI [8]. Sample was used in the horizontal orientation with the edge frame and spark igniter. Tests were generally conducted in duplicate at three heat flux levels: 20, 35, and 50 kW/m^2. A third test was performed if there was a large discrepancy. Up to four additional ignition tests were performed at heat flux levels below 20 kW/m^2. Most samples used were 100-mm x100-mm in dimension with a thickness > 6-mm. Supplemental toxic gas measurements for the concentrations and yields of CO, CO_2, HCN, NO_x, and HCl were made in the sampling duct of the Cone Calorimeter by an FTIR. The measured data are listed in Tables A-4-9 to A-4-13.

5. Data from the Tests in the Fire Propagation Apparatus Following the ASTM E2058 Standard Test Procedures

The tests were performed by FM Global following the ASTM E2058 standard test procedure. [12,13,14,16,17,19]. For the ignition and combustion tests, square (100-mm x 100-mm) or round (100-mm diameter) samples with thickness > 3-mm. were used in a horizontal orientation.

Ignition tests were performed in normal air with external heat flux in the range of 10 to 60 kW/m^2. Combustion tests were performed in normal air with an external heat flux of 50 kW/m^2. For fire propagation tests performed in 40 % oxygen concentration and 50 kW/m^2 of external heat flux, 100-mm wide, 300-mm high samples in a vertical orientation with thickness ≥ 3-mm were used. The measured data are listed in Tables A-4-14 to A-4-18.

Table A-4-1. The FMVSS 571.302 Test Data for Plastics in a 1996 Dodge Caravan Parts [8]

Part	Description	Plastic	Behavior	Test Run			Burn Rate (mm/min)	Pass/Fail
				1	2	3		
5235267AB	Battery Cover	PP	Flaming droplets (sec)	36	23	24	68	Pass
4861057	Resonator Structure	PP	Melting (s)	114			51	Pass
			Dripping (s)	120	108			
			Burning on the floor (s)	152	120			
5303058	Resonator Intake Tube	EPDM Rubber	Flaming droplets (s)	26			56	Pass
4678345	Air Ducts	PE or PP	Flaming droplets (s)	46	36		37	Pass
4683264	Brake Fluid Reservoir	PP	Dripping (s)	64			20	Pass
			Burning on the floor (s)	244				
4860446	Kick Panel Insulation	PVC	No sustained burning				0	Pass
4857041A	Headlight Clear Lens	PC						
4857041A	Headlight Casing	POM	No sustained burning				0	Pass
4716345B	Fender Sound Reduction foam	PS	Flaming droplets (s)	413	368		36	Pass
4716832B	Hood Liner Face	PET	No sustained burning				0	Pass
4716051	Windshield Wiper Structure	Fiberglass/ Polyester/styrene	No sustained burning				0	Pass

Table A-4-2. The FMVSS 571.302 Test Data for Plastics in a 1997 Chevrolet Camaro Parts (8)

Part	**Description**	**Plastic**	**Behavior**	**Test Run**			**Burn Rate (mm/min)**	**Pass/ Fail**
				1	**2**	**3**		
10296526	Front Wheel Well Liner	PP,PE	Dripping (s)	45	39		37	Pass
			Flaming droplets (s)	52	50			
			Burning on the floor (s)	186	162			
10297291	Air Inlet	PP,PE	Flaming droplets (s)		105	105	15	Pass
			Burning on floor (s)		105	105		
10278015	Hood Insulator	Nylon 6/ phenolic binder	No sustained burning				0	Pass
52465337	Radiator Inlet/Outlet Tank	Nylon 6,6	Dripping	no	No sustained burning		2	Pass
			Flaming	no				
22098787	Engine Cooling Fan	Nylon6	No sustained burning				0	Pass
26019594	Power Steering Fluid Reservoir	Nylon 6,6	No sustained burning				0	Pass
10310333	Windshield Laminate		No sustained burning				0	Pass
52458965	Blower Motor Housing	PP	Flaming droplets (s)	37	41		32	Pass

Table A-4-3. Peak CO and HCl Concentrations and Yields (Airbus Method at 25 kW/m^2) [8]

Part	Plastic	Measurement	Mode	CO			HCl		
				1	2	Av	1	2	Av
Headlight lens (4857041A	PC	Concentration (ppm)	NF	4	2	3			
			F	470	532	501			
		Yield (mg/g)	NF	2	1	2			
			F	22	29	26			
Hood liner face 4716832B	PET	Concentration (ppm)	NF	2563	2095	2329			
			F	2096	1765	1931			
		Yield (mg/g)	NF	82	61	71			
			F	93	71	82			
Kick panel backing-rubber side 4860446	PVC	Concentration (ppm)	NF	528	731	629	510	631	571
			F	1053	934	994	625	596	611
		Yield (mg/g)	NF	10	12	11	22	32	27
			F	28	31	30	26	28	27

Table A-4-4. Peak CO and HCl Concentrations and Yields (IMO Method at 25 kW/m^2) [8]

Part	Plastic	Measurement	Mode	CO			HCl		
				1	2	Av	1	2	Av
Headlight lens (4857041A	PC	Concentration (ppm)	NF	1	4	2			
			F	14	19	17			
		Yield (mg/g)	NF	1	1	1			
			F	2	4	3			
Hood liner face 4716832B	PET	Concentration (ppm)	NF	5860	4400	5130			
			F	3470	4020	3745			
		Yield (mg/g)	NF	228	131	179			
			F	133	91	112			
Kick panel backing-rubber side 4860446	PVC	Concentration (ppm)	NF	174	3	89	41	30	36
			F	362	9	185	27	11	19
		Yield (mg/g)	NF	48	3	25	14	10	12
			F	7	2	4	1	4	3

Table A-4-5. Peak CO and HCl Concentrations and Yields (IMO Method: Non-Flaming) at 50 kW/m^2 [8]

Part	Plastic	Measurement	CO			HCl		
			1	2	Av	1	2	Av
Headlight lens (4857041A)	PC	Concentration (ppm)	1845	838	1342			
		Yield (mg/g)	63	85	74			
Hood liner face 4716832B	PET	Concentration (ppm)	4189	2874	3532			
		Yield (mg/g)	139	160	150			
Kick panel backing-rubber side 4860446	PVC	Concentration (ppm)	964	1012	988	1073	1251	1162
		Yield (mg/g)	15	34	25	18	80	49

Table A-4-6. Thermal Behavior of Plastics at Ambient Temperature (GM 9833P Test) [15]

Temperature °C	Thermal Behavior	Polypropylene			Nylon 6		Nylon 66 Ultramid A3X2G5 (FR)
		Pro-fax 8523	151 (FR)	156 (FR)	Standard	With nano-composite	
20	Mass Loss (%)	29.9	2.4	3.2	3.9	7.4	1.1
93		31.0	1.9	2.7	8.6	23.2	1.7
121		57.5	4.6	4.6	11.0	30.6	1.9
150		72.1	7.3	7.4	12.4	34.0	2.2
20	Burning (%)	5.5	1.3	2.0	3.4	5.4	1.0
93		1.1	1.0	1.8	0.8	3.1	1.2
121		18.2	2.9	2.8	0.3	4.8	0.8
150		10.4	4.3	4.6	0.4	3.8	0.6
20	Dripping (%)	24.4	1.1	1.2	0.5	2.0	0.1
93		29.9	0.9	0.9	7.8	20.1	0.5
121		39.3	1.7	1.8	10.7	25.8	1.1
150		61.7	3.0	2.8	12.0	30.2	1.6

Table A-4-7. Thermal Behavior of Plastics at 121 °C (GM 9833P Test) [15]

Plastic	**$W_{initial}$ (g)**	**W_{final} (g)**	**W_{loss}**		**$W_{burning}$ (%)**	**Maximum Dripping**	
			g	**%**		**g**	**%**
Polypropylene							
SB-786	122.7	75.0	47.7	38.9	17.8	25.8	21.1
8523	73.5	35.4	42.1	57.5	21.1	26.8	36.4
151 (FR)	102.6	100.8	1.8	1.7	1.0	0.7	0.7
156 (FR)	139.8	136.5	3.3	2.4	1.9	0.6	0.4
Nylon 66							
A3K	91.5	81.0	12.5	13.7	5.8	7.2	7.8
A3X2G5 (FR)	102.6	100.8	1.8	1.7	0.4	1.4	1.3
200H (FR)	127.6	123.2	4.4	3.4	3.2	0.2	0.2
299X	116.9	107.3	9.6	8.2	8.0	0.2	0.2
Nylon 6							
Standard	97.0	86.3	10.7	11.0	0.1	10.6	10.9
With nano composite	107.0	76.0	31.0	29.0	6.4	24.1	22.6

Table A-4-8. Flame Spread Behavior of Plastics (GM 9833P Test)[3]

Plastic	Ignition Attempts	Weight Loss (%)		Flame spread		Observations
		Dripping	Burning	Distance (%)	Rate (mm/s)	
Polypropylene						
Profax SB 786	1	11.0	5.2	71	0.93	Flammable, burning drops
Profax 8523	1	27.5	2.4	94	2.48	Flammable, burning drops
151 (FR)	5	0.7	0.7	13	0.08	5 s flaming without dripping
156 (FR)	5	1.2	2.0	21	0.12	Dripping after 35 seconds with non-burning drops
Nylon 66						
Ultramid A3K	1	7.7	1.3	21	0.73	Flammable, burning drops
Ultramid A3X2G5 (FR)	8	0.0	2.9	4	0.00	Non- flammable, No dripping
200H (FR)	9	0.0	2.5	4	0.00	Non- flammable, No dripping
299X	8	0.5	2.8	9	0.04	Flaming while lighting, No dripping
Nylon 6						
Standard	4	0.5	3.5	13	0.04	8 drops at second Ignition
With nano composite	2	2.0	7.0	34	0.17	Flammable, very little dripping

Table A-4-9. The ASTM E1354 Cone Calorimeter Test Data for Time to Ignition, Burn and Peak Heat Release Rate [8]

Part	Description	Flux (kW/m^2)	20	35	50	20	35	50	20	35	50
		Plastic	**Time-to-Ignition (s)**			**Burn Time (s)**			**Time-to-Peak Heat Release Rate (s)**		
1996 Dodge Caravan											
4857041A	Headlight Assembly (clear)	PC	NI	428	66	NI	355	403	1110	523	193
5235267AB	Battery Cover	PP	155	24	8	314	152	130	212	75	43
4861057	Resonator Structure	PP	149	44	19	546	600	310	265	218	125
53030508	Resonator Intake Tube	EPDM Rubber	113	26	14	675	358	210	195	80	68
4678345	Air Ducts	PE or PP	90	34	16	446	424	409	193	170	85
4683264	Brake Fluid Reservoir	PP	147	57	36	387	449	248	285	165	128
4860446	Kick Panel Insulation	PVC	52	32	23	586	604	418	194	175	80
4857041A	Headlight Assembly (Black)	PC	NI	766	32	NI	353	314	538	803	165
4716345B	Fender Sound Reduction foam	PS	4	2	1	268	222	124	96	104	43
4716832B	Hood Liner Face	PET	18	6	4	60	324	584	232	38	20
4716051	Windshield Wiper Structure	Fiberglass/polyester /styrene	152	82	45	341	515	255	223	143	83
1997 Chevrolet Camaro											
10296526	Front Wheel Well Liner	PP, PE	107	37	18	624	563	532	170	133	78
10297291	Air Inlet	PP, PE	115	39	16	578	444	343	223	145	95
10278015	Hood Insulator	Nylon6/ phenolic binder	10	2	2	8	8	8	281	22	368
52465337	Radiator Inlet/Outlet Tank	Nylon 6,6	306	98	44	1026	574	396	723	238	135
22098787	Engine Cooling Fan	Nylon6	370	140	34	1386	1210	406	715	523	85
26019594	Power Steering Fluid Reservoir	Nylon 6,6	NI	169	36	NI	605	538	1116	291	138
10310333	Windshield Laminate		358	106	62	434	301	246	490	195	130
52458965	Blower Motor Housing	PP	138	46	24	822	372	296	285	159	108

Table A-4-10. The ASTM E1354 Cone Calorimeter Test Data for the Mass Loss Rate and Heat Release Rate [8]

Part	**Description**	**Flux (kW/m^2)**	**20**	**35**	**50**	**20**	**35**	**50**
		Plastic	**Mass Loss Rate (g/m^2-s)**			**Heat Release Rate (kW/m^2)**		
1996 Dodge Caravan								
4857041A	Headlight Assembly (clear)	PC	0.1	14.8	16.2	12	431	401
5235267AB	Battery Cover	PP	4.3	7.5	8.1	226	324	384
4861057	Resonator Structure	PP	7.9	9.4	12.9	354	380	517
53030508	Resonator Intake Tube	EPDM Rubber	3.7	6.6	11.7	335	368	599
4678345	Air Ducts	PE or PP	6.7	11.3	10.0	460	524	697
4683264	Brake Fluid Reservoir	PP	8.9	10.1	13.3	333	526	626
4860446	Kick Panel Insulation	PVC	3.9	5.3	4.8	180	213	224
4857041A	Headlight Assembly (Black)	PC	0.1	2.7	13.3	5	158	312
4716345B	Fender Sound Reduction foam	PS	6.4	15.0	9.3	184	262	307
4716832B	Hood Liner Face	PET	3.6	4.2	2.7	44	71	83
4716051	Windshield Wiper Structure	Fiberglass/polyester/ styrene	6.7	5.7	9.8	212	164	323
1997 Chevrolet Camaro								
10296526	Front Wheel Well Liner	PP, PE	4.0	4.6	4.8	299	335	526
10297291	Air Inlet	PP, PE	6.9	10.7	11.1	418	693	759
10278015	Hood Insulator	Nylon6/phenolic binder	0.0	0.0	0.0	13	16	19
52465337	Radiator Inlet/Outlet Tank	Nylon 6,6	5.1	10.4	13.8	197	376	458
22098787	Engine Cooling Fan	Nylon6	1.2	4.1	9.3	49	131	294
26019594	Power Steering Fluid Reservoir	Nylon 6,6	0.3	5.1	9.3	7	216	499
10310333	Windshield Laminate	Fiberglass/polyester/ styrene	2.5	4.6	5.5	96	194	269
52458965	Blower Motor Housing	PP	4.2	6.9	8.4	214	262	328

Table A-4-11. The ASTM E1354 Cone Calorimeter Test Data for the Chemical Heat of Combustion and Yields of Smoke and CO at Various External Heat Flux Values

Part	Description	Plastic	ΔH_{ch} (kJ/g)			y_s (g/g)			y_{co} (g/g)
			Heat Flux (kW/m^2)						
			20	35	50	20	35	50	50
1996 Dodge Caravan									
4857041A	Headlight Assembly (clear)	PC	66.1	19.5	19.4	0.401	0.064	0.070	0.050
5235267AB	Battery Cover	PP	32.1	36.1	35.9	0.025	0.046	0.054	0.013
4861057	Resonator Structure	PP	36.7	34.1	36.4	0.054	0.050	0.066	0.028
53030508	Resonator Intake Tube	EPDM Rubber	35.1	27.5	34.7	0.046	0.044	0.055	0.021
4678345	Air Ducts	PE or PP	37.0	34.3	37.0	0.049	0.042	0.057	0.024
4683264	Brake Fluid Reservoir	PP	29.1	35.4	35.9	0.040	0.051	0.055	0.025
4860446	Kick Panel Insulation	PVC	25.4	26.4	27.9	0.028	0.035	0.046	
4857041A	Headlight Assembly	PC	24.5	17.4	19.4	0.253	0.042	0.072	0.054
4716345B	Fender Sound Reduction foam	PS	24.4	26.8	27.7	0.087	0.103	0.116	0.052
4716832B	Hood Liner Face	PET	6.3	11.5	14.9	0.030	0.004	0.008	
4716051	Windshield Wiper Structure	Fiberglass/polyester /styrene	20.9	17.9	21.0	0.070	0.057	0.076	0.036
1997 Chevrolet Camaro									
10296526	Front Wheel Well Liner	PP,PE	33.4	24.4	35.2	0.029	0.026	0.037	0.031
10297291	Air Inlet	PP,PE	32.9	37.4	35.7	0.029	0.041	0.054	0.021
10278015	Hood Insulator	Nylon6/phenolic binder	5.3	162.0	13.5	0.026	0.469	0.089	0.050
52465337	Radiator Inlet/Outlet Tank	Nylon 6,6	24.7	26.3	25.5	0.028	0.027	0.030	
22098787	Engine Cooling Fan	Nylon6	26.7	25.7	25.6	0.017	0.020	0.018	
26019594	Power Steering Fluid Reservoir	Nylon 6,6	5.8	21.8	29.8	0.012	0.026	0.043	
10310333	Windshield Laminate		24.1	23.9	24.4	0.019	0.019	0.019	
52458965	Blower Motor Housing	PP	32.7	32.6	35.6	0.032	0.047	0.065	0.025

Table A-4-12 Ignition and Combustion Properties from the ASTM E 1354 Cone Calorimeter Tests

Part	Description	Plastic	Ignition		Combustion					
			CHF (kW/m^2)	TRP ($kW-s^{1/2}/m^2$)	ΔH_{ch} (kJ/g)	y (g/g)				
						Smoke	CO	HCN	NO_x	HCl
1996 Dodge Caravan										
4857041A	Headlight Assembly	PC	23	200	19.5	0.067	0.050			
5235267AB	Battery Cover	PP	19	100	36.0	0.050	0.013			
4861057	Resonator Structure	PP	11	192	35.7	0.057	0.028			
53030508	Resonator Intake Tube	EPDM Rubber	11	204	32.4	0.048	0.021			
4678345	Air Ducts	PE or PP	12	189	36.1	0.049	0.024			
4683264	Brake Fluid Reservoir	PP	9	427	33.5	0.049	0.025			
4860446	Kick Panel Insulation	PVC	15	492	26.6	0.041	0.009			0.003
4857041A	Headlight Assembly	PC	37	112	20.4	0.057	0.054			
4716345B	Fender Sound Red foam	PS	9	89	26.3	0.102	0.052			
4716832B	Hood Liner Face	PET	14	114	13.2	0.006	0.142			
4716051	Windshield Wiper Structure	Fiberglass/polyester/styrene	11	381	19.9	0.068	0.036			
1997 Chevrolet Camaro										
10296526	Front Wheel Well Liner	PP,PE	8	220	31.0	0.031	0.031			
10297291	Air Inlet	PP,PE	10	174	35.3	0.041	0.021			
10278015	Hood Insulator	Nylon6/ phenolic binder	19	39	13.5	0.089	0.050			
52465337	Radiator Inlet/Outlet Tank	Nylon 6,6	18	297	25.5	0.028	0.013	0.005	0.015	
22098787	Engine Cooling Fan	Nylon6	18	172	26.0	0.018	0.015	0.005	0.012	
26019594	Power Steering Fluid Reservoir	Nylon 6,6	21	159	25.8	0.035	0.026	0.006	0.001	
10310333	Windshield Laminate		16	238	24.1	0.019	0.003			
52458965	Blower Motor Housing	PP	8	275	33.6	0.048	0.025			

Table A-4-13. Thermal Behavior and Heat Release Parameter of Plastics from the ASTM E 1354 Cone Calorimeter Test Data

Part	Description	Plastic	Behavior	HRP
1996 Dodge Caravan				
4857041A	Headlight Assembly (clear)	PC	Softening	9
5235267AB	Battery Cover	PP	Melting	8
4861057	Resonator Structure	PP	Melting	11
53030508	Resonator Intake Tube	EPDM Rubber	Charring	12
4678345	Air Ducts	PE or PP	Melting	15
4683264	Brake Fluid Reservoir	PP	Melting	14
4860446	Kick Panel Insulation	PVC	Charring	5
4857041A	Headlight Assembly (Black)	PC	Softening	5
4716345B	Fender Sound Reduction foam	PS	Softening	7
4716832B	Hood Liner Face	PET	Softening	(2)
4716051	Windshield Wiper Structure	Fiberglass/polyester/ styrene	Charring	6
1997 Chevrolet Camaro				
10296526	Front Wheel Well Liner	PP, E	Melting	11
10297291	Air Inlet	PP, PE	Melting	17
10278015	Hood Insulator	Nylon 6/phenolic binder	Non-melting	(0.20)
52465337	Radiator Inlet/Outlet Tank	Nylon 6,6	Softening	10
22098787	Engine Cooling Fan	Nylon 6	Non-melting	5
26019594	Power Steering Fluid Reservoir	Nylon 6,6	Softening	8
10310333	Windshield Laminate	Polyvinyl butyral	Softening	5
52458965	Blower Motor Housing	PP	Softening	7

Table A-4-14. Combustion Data from the Tests at 50 kW/m^2 in Normal Air in the ASTM E 2058 FPA for the Plastics in a 1996 Dodge Caravan Parts (16,17)

Part	Plastic	Behavior	W_f (g)	Residue (%)	$\dot{m}_f''$ (g/m^2-s)	$\dot{G}_j''$ (g/m^2-s)				$\dot{Q}_{ch}''$ (kW/m^2)
						CO	CO_2	Hydro	Smoke	
GJ42SK4D	Nylon 6	Melting	4.4	1.1	8.9	0.40	22.5	0.01	0.66	301
JF48SK5B	PVC	Charring	39.1	6.3	21.7	1.42	37.3	0.21	3.08	527
PL98SX8A	PC	Softening	25.9	4.2	27.9	1.26	44.7	0.08	3.29	486
4612512A	PP	Melting	17.4	15.7	25.7	1.00	66.2	0.08	2.09	926
4612512B	EPDM	Charring	27.4	16.9	9.1	0.60	18.0	0.01	0.91	242
4674711B	PVC	Charring	15.9	51.8	15.0	1.05	15.6	0.12	1.64	219
4678345B	PP	Melting	14.7	2.3	31.6	1.95	78.8	0.36	2.86	1110
4680250A	Rubber	Charring	10.3	4.6	16.2	0.79	29.2	0.05	3.34	396
4680250C	polyester	Charring	14.9	4.1	17.2	0.53	36.3	0.03	1.51	488
4683264	PP	Melting	14.9	0.0	35.1	3.52	88.3	1.17	3.35	1254
4707580A	HDPE	Melting	15.0	0.0	35.5	3.95	93.1	1.40	2.52	1341
4716051	SMC	Charring	11.0	70.5	14.4	0.61	25.5	0.03	2.26	345
4716345B	PS	Softening	8.8	30.6	17.5	0.64	28.1	0.07	2.34	381
4716832B	PET	Softening	10.1	5.3	7.8	0.34	9.74	0.03	0.75	132
4716895	PP	Melting	11.7	1.1	26.7	1.43	77.0	0.16	2.35	1078
4716896A	Fibers	Non-melting	7.9	67.7	7.5	0.57	9.5	0.01	0.30	128
4734071	PP	Softening	11.6	4.3	21.1	0.78	54.0	0.08	1.73	755
4734370	ABS/PVC	Charring	9.0	1.2	8.7	0.60	11.5	0.03	1.08	158
4857041A	PC	Softening	26.9	5.8	31.9	1.74	51.2	0.21	4.75	559
4883140A	PE	Melting	31.6	4.0	37.4	2.34	91.4	0.57	2.04	1296
5235267	PP	Melting	15.2	0.1	26.0	1.64	71.4	0.23	2.40	1004

Table A-4-15 Combustion Data from the Tests at 50 kW/m^2 in Normal Air in the ASTM E 2058 FPA for the Plastics in a 1997 Chevrolet Camaro Parts (16,17)

Part	Plastic	Behavior	W_f (g)	Residue (%)	$\dot{m}''_f$ (g/m^2-s)	$\dot{G}''_j$ (g/m^2-s)				$\dot{Q}''_{ch}$ (kW/m^2)
						CO	CO_2	Hydro	Smoke	
10231299	PU	Softening	20.8	19.4	33.2	0.83	69.87	0.04	2.57	936
10243962	PP/PE	Melting	17.4	0.0	38.0	4.71	86.49	2.34	3.25	1191
10246204	PP/PE	Melting	17.9	2.6	33.8	4.22	91.95	1.69	3.96	1263
10269100	ABS	Melting	31.7	9.2	22.2	1.29	41.30	0.18	3.80	563
10278015		Non-Melting	1.8	60.0	2.5	0.51	5.71	0.03		77
10278989	Nylon 6	Softening	25.0	13.8	21.4	0.49	46.10	0.04	1.57	618
10284967		Softening	29.1	24.6	23.4	0.61	44.81	0.03	2.03	602
10296526	PP/PE	Melting	17.7	0.0	spill	4.55	88.57	1.95	3.81	1218
16514312	PE	Melting	16.2	0.0	spill	2.40	84.16	0.52	2.76	1144
22098787	Nylon 6/6	Non-Melting	18.3	34.9	17.1	0.42	39.74	0.06	0.74	531
52458712		Softening	11.2	36.2	24.2	1.10	60.39	0.10	2.38	
52458713	PP	Softening	10.2	35.5	23.5	1.12	62.34	0.12	2.37	841
52458898	PP	Softening	11.3	35.8	20.1	0.83	53.64	0.06	1.97	
52458965	PU	Softening	11.1	13.1	24.3	1.18	63.90	0.16	2.74	862
52458976	PU	Non-Melting	13.8	50.2	21.5	0.64	40.00	0.03	1.67	539
52465340	Nylon 6/6	Non-Melting	16.8	23.0	15.9	0.51	36.36	0.01	1.03	486

Table A-4-16 Ignition, Flame Spread and Combustion Properties and Behavior from Tests in the ASTM E 2058 FPA for the Plastics in a 1996 Dodge Caravan Parts (16,17)

Part	**Plastic**	**Ignition and Flame Spread**			**Combustion**					
		CHF (kW/m^2)	**TRP ($kW\text{-}s^{1/2}/m^2$)**	**FPI($m/s^{1/2}$)/ (kW/m)$^{2/3}$**	**Behavior**	**y_j (g/g)**				**ΔH_{ch} (kJ/g)**
						CO	**CO_2**	**HC**	**Smoke**	
GJ42SK4D	Nylon 6	20	154	26	Melting	0.086	2.09	0.001	0.045	28.8
JF48SK5B	PVC	10	263	15	Charring	0.057	1.72	0.005	0.109	24.4
PL98SX8A	PC	20	357	11	Softening	0.051	1.86	0.002	0.105	20.2
4612512A	PP	10	277	14	Melting	0.041	2.46	0.002	0.072	34.6
4612512B	EPDM	a	a	a	Charring	0.045	2.51	0.001	0.100	33.8
4674711B	PVC	10	215	18	Charring	0.061	1.26	0.006	0.070	17.4
4678345B	PP	15	230	11	Melting	0.056	2.52	0.004	0.080	35.5
4680250A	NR	a	a	a	Charring	0.061	1.87	0.003	0.130	25.6
4680250C	Polyester	a	a	a	Charring	0.039	2.17	0.002	0.087	29.4
4683264	PP	a	a	a	Melting	0.058	2.41	0.011	0.072	33.9
4707580A	HDPE	a	a	a	Melting	0.064	2.67	0.012	0.058	38.2
4716051	SMC	20	483	8	Charring	0.061	1.86	0.003	0.100	25.5
4716345B	PS	20	146	27	Softening	0.064	1.80	0.002	0.098	24.6
4716832B	PET	10	174	23	Softening	0.041	1.47	0.003	0.022	20.0
4716895	PP	15	288	13	Melting	0.054	2.45	0.002	0.065	34.5
4716896A	Fibers	15	430	4	Non-melting	0.098	1.75	0.003	0.006	18.4
4734071	PP	15	310	12	Softening	0.057	2.49	0.002	0.060	35.0
4734370	ABS-PVC	19	73	57	Charring	0.089	1.62	0.001	0.060	22.6
4857041A	PC	20	434	9	Softening	0.049	1.67	0.004	0.113	18.2
4883140A	PE	15	454	8	Melting	0.032	2.33	0.005	0.042	32.7
5235267	PP	15	323	12	Melting	0.045	2.59	0.004	0.071	36.2

Table A-4-17. Ignition, Flame Spread and Combustion Properties and Behavior from Tests in the ASTM E 2058 FPA for the Plastics in a 1997 Chevrolet Camaro Parts (16,17)

Part	Plastic	Ignition and Flame Spread			Combustion					
		CHF (kW/m^2)	TRP ($kW\text{-}s^{1/2}/m^2$)	FPI($m/s^{1/2}$)/ (kW/m)$^{2/3}$	Behavior	y_j (g/g)				ΔH_{ch} (kJ/g)
						CO	CO_2	HC	Smoke	
10231299	PU	10	204	18	Softening	0.038	2.01	0.001	0.074	25.7
10243962	PP/PE	15	351	12	Melting	0.087	2.58	0.018	0.097	33.6
10246204	PP/PE	10	239	17	Melting	0.071	2.76	0.013	0.119	36.0
10269100	ABS	10	263	12	Melting	0.066	1.85	0.005	0.170	19.4
10278015	Fibers	25	135	-	Non-Melting	0.478	0.483	0.016	0.094	5.8
10278989	Nylon 6	13	197	17	Softening	0.027	2.11	0.001	0.072	28.3
10284967		10	310	10	Softening	0.040	2.01	0.001	0.091	25.8
10296526	PP/PE	15	415	10	Melting	0.080	2.51	0.017	0.108	33.3
16514312	PE	15	396	11	Melting	0.065	2.59	0.007	0.085	34.6
22098787	Nylon 6/6	20	359	10	Non-Melting	0.024	2.19	0.001	0.041	27.9
52458712		15	360	10	Softening	0.063	2.56	0.003	0.101	32.4
52458713	PP	15	329	11	Softening	0.058	2.58	0.002	0.098	32.6
52458898	PP	15	379	10	Softening	0.054	2.69	0.002	0.099	30.44
52458965	PU	15	337	11	Softening	0.065	2.68	0.003	0.115	33.9
52458976	PU	15	369	9	Non-Melting	0.057	2.04	0.002	0.085	25.3
52465340	Nylon 6/6	27	408	9	Non-Melting	0.039	2.11	0.001	0.060	26.6

Table A-4-18. Ignition, Flame Spread and Combustion Properties and Behavior from Tests in the ASTM E 2058 FPA for the Replacements Plastics for Vehicle Parts (16,17)

Characteristics	**Polypropylene**			**Nylon 66**			
	Profax SB 786	**Profax 523**	**156 (FR)**	**299X**	**200H (FR)**	**Ultramid A3K**	**Ultramid A3X2G5(FR)**
Ignition and Flame Spread Properties							
CHF (kW/m^2)	10	10	10	18	12	10	10
TRP (kW-s$^{1/2}$/m^2)	282	376	350	311	423	239	218
FPI (m/s$^{1/2}$)/(kW/m)$^{2/3}$	20	13	13	22	12	27	21
Combustion Behavior and Properties							
Behavior	Non-melting	Melting	Melting	Melting	Softening	Melting	Non-melting
$\dot{m}''_f$ (g/m^2-s)	8.6	9.0	13.6	11.4	17.5	15.4	7.9
$\dot{G}''_{CO}$ (g/m^2-s)	0.35	0.46	2.5	0.35	2.74	0.64	0.94
$\dot{G}''_{CO_2}$ (g/m^2-s)	23.9	23.8	11.7	27.0	16.0	36.8	13.1
$\dot{G}''_{sm}$ (g/m^2-s)	1.1	1.2	3.7	0.71	4.0	0.90	1.2
$\dot{Q}''_{ch}$ (kW/m^2)	332	344	185	361	242	491	184
y_{co} (g/g)	0.07	0.08	0.20	0.03	0.16	0.06	0.17
y_{co2} (g/g)	3.13	2.97	1.00	2.16	1.20	2.21	1.83
y_{sm} (g/g)	0.11	0.12	0.23	0.04	0.18	0.04	0.16
X_{flame} (m)	500	500	360	500	400	500	360
ΔH_{ch} (kJ/g)	39.0	38.6	14.1	27.7	17.1	28.4	24.0

APPENDIX B-1

TEST METHODS USED IN THE QUANTIFICATION OF THE ENGINE COMPARTMENT FLUID PROPERTIES

(References in Chapter II)

1. ASTM D287-92 STANDARD TEST METHOD FOR API GRAVITY[1] OF FLUIDS

The Test Method is based on the principle that the gravity of a fluid varies directly with the depth of immersion of a body floating in it [7]. The floating body, which is graduated by API gravity units, is called an API hydrometer.

A glass hydrometer is used to determine the API gravity of crude petroleum and petroleum products normally handled as liquids and having a Reid vapor pressure of 26-psi (180 kPa) or less. The API gravity is read by observing the freely floating API hydrometer in a glass cylinder filled with the test fluid. The graduations are noted nearest to the apparent intersection of the horizontal plane surface of the fluid with the vertical scale of the hydrometer, after temperature equilibrium has been reached. A thermometer measures the fluid temperature.

API gravity is determined at 60 ^{o}F (15.56 ^{o}C) or converted to the value at 60 ^{o}F, by means of standard tables. The API gravity values of fluids by this Test Method were measured by UEC[2] [11].

2. ASTM D1120-94 STANDARD TEST METHOD FOR THE BOILING POINT OF ENGINE COOLANTS

The Test Method is based on the principle that the equilibrium boiling point indicates the temperature at which the sample will start to boil in a cooling system under equilibrium conditions at atmospheric pressure [7]. In the Test Method, 60 mL of the fluid are boiled under equilibrium conditions at atmospheric pressure in a 100 mL flask attached to a condenser. The fluid is heated in the flask by an electric mantle and the fluid temperature is measured by a thermometer. The heating of the mantle is adjusted such that the reflux rate of the boiling fluid is 1 to 2 drop per second and the temperature is recorded. This temperature of the fluid corrected for the barometric pressure is taken as the boiling point of the fluid. The boiling points of the engine compartment fluids by this Test Method were measured by UEC [11].

---

[1] API gravity is an arbitrary scale calibrated in degree and related to the specific gravity at 15.56/15.56^{o}C (60/60^{o}F) by the following expression [7]: API specific gravity, deg = (141.5/specific gravity 60/60 ^{o}F)-131.5.

[2] UEC Fuels and Lubrication Laboratories, Monroeville, PA.

3. ASTM D86-96 STANDARD TEST METHOD FOR THE DISTILLATION OF PETROLEUM PRODUCTS [7]

The Test Method is based on the principle that the equilibrium boiling point indicates the temperature at which the sample will start to boil in a cooling system under equilibrium conditions at atmospheric pressure. The Method is intended for the distillation of natural gasoline, motor gasoline, aviation gasoline, aviation turbine fuels, special boiling point spirits, naphtha, white spirit, kerosene, gas oils, distillate fuel oils, and similar petroleum products.

In the Test Method, 100 mL of the fluid are distilled under prescribed conditions that are appropriate to the nature of the fluid using a distillation flask attached to a condenser. Systematic observations of thermometer readings and volumes of condensate are made and are used in the calculations. For example, thermometer readings are recorded at prescribed percentages of fluid recovered and/or percentages recovered are recorded at prescribes thermometer readings. The endpoint or the final boiling point is also recorded. The temperatures are corrected for the barometric pressures. The data are reported for initial boiling point ($\mathbf{T_{ib}}$), final boiling point ($\mathbf{T_{fb}}$) and percent distillation at various temperatures. Measurements using this Test Method were made by UEC [11].

4. ASTM D2887-01 STANDARD TEST METHOD FOR BOILING RANGE DISTRIBUTION OF PETROLEUM FRACTIONS BY GAS CHROMATOGRAPHY

The Test Method is based on the principle that the boiling range distribution by distillation can be simulated by the use of a gas chromatograph (GC) [7]. A non-polar packed or open tubular (capillary) GC column is used to elute the hydrocarbon components of the fluid in order of increasing boiling point. The column temperature is increased at a reproducible linear rate and the area under the chromatogram is recorded throughout the analysis. Boiling points are assigned to the time axis from the calibration curve obtained under the same chromatographic conditions by analyzing the calibration mixture consisting of hydrocarbons covering the range expected in the sample. The Test Method utilizes a calibration mixture[3] that consists of equal masses of n-hydrocarbons including n-C_5 to n-C_{44} in carbon disulfide. At least one compound in the mixture

---

[3] Additional calibration mixture that was gravimetrically prepared by mixing paraffins, isoparaffins, aromatics, naphthalene, and olefins (PIANO) was used in the GM sponsored projects [8].

has a boiling point lower than the initial boiling point of the fluid. From measured data, the boiling range distribution is obtained.

In the Test Method, 0.2 to 2.0 μL of the fluid sample are injected into the GC. All the integrated GC detector responses for each time interval and for the total test time are added. The temperature for the 0.5 % of the total integrated GC detector responses is used as the initial boiling point ($\mathbf{T_{ib}}$) of the fluid and the temperature for the 99.5 % of the total integrated GC detector responses is used as the final boiling point ($\mathbf{T_{fb}}$) of the fluid. Division of the integrated GC detector responses for each time interval by the integrated GC detector responses for total test time interval is used to calculate the percent of sample recovered at each time or temperature interval. Measurements using this Test Method were made by GM [8] and by UEC [11].

5. MODULATED DIFFERENTIAL SCANNING CALORIMETRY (MDSC) FOR THE VAPORIZATION OF THE ENGINE COMPARTMENT FLUIDS

The Modulated Differential Scanning Calorimeter (MDSC) provides a rapid method for the determination of enthalpy changes accompanying first order transitions for fluids [10]. The heat flow associated with vaporization and boiling is recorded and integrated over time. In the Test Method, a test specimen is heated at a controlled rate in a well-defined environment in a DSC through the temperature region of vaporization and boiling. From the enthalpy changes, measurements are made for the boiling point ($\mathbf{T_b}$) and heat of vaporization ($\mathbf{\Delta H_v}$) of the engine compartment fluids, using a fluid of known $\mathbf{T_b}$ and $\mathbf{\Delta H_v}$ values, such as toluene, as an internal standard.

In the Test Method, a hermitic sealed aluminum pan with pinhole of 0.8-mm in diameter was used as fluid sample container. A 1.4-mm diameter steel ball on top of the sealed pan was used as a “valve” for reproducible measurements of the boiling process. The measurements were made from 15 °C to 520 °C. The heating rate was set to 5 °C/minute and the degree of modulation was set at ± 0.8 °C, every 60 seconds. A five-minute isothermal period preceding and ending each test was used to establish equilibrium points between sample, baseline, and reference run.

6. ASTM D93-97 STANDARD TEST METHOD FOR THE FLASH POINT OF FLUIDS (PENSKY-MARTENS CLOSED CUP)

The test apparatus is shown in Fig. B-1 [7]. It consists of a closed 54-mm (2.1-in) wide and 56-mm (2.2-in) deep brass cup heated electrically. The cover of the cup has provisions for introducing a thermocouple, a stirrer, and a shutter with a pilot flame. The fluid is stirred in the cup as it is heated. The shutter has a control mechanism to lower the flame into the vapor space of the test cup in 0.5 second, keep it in the lowered position for one second, and quickly move it to its upward position.

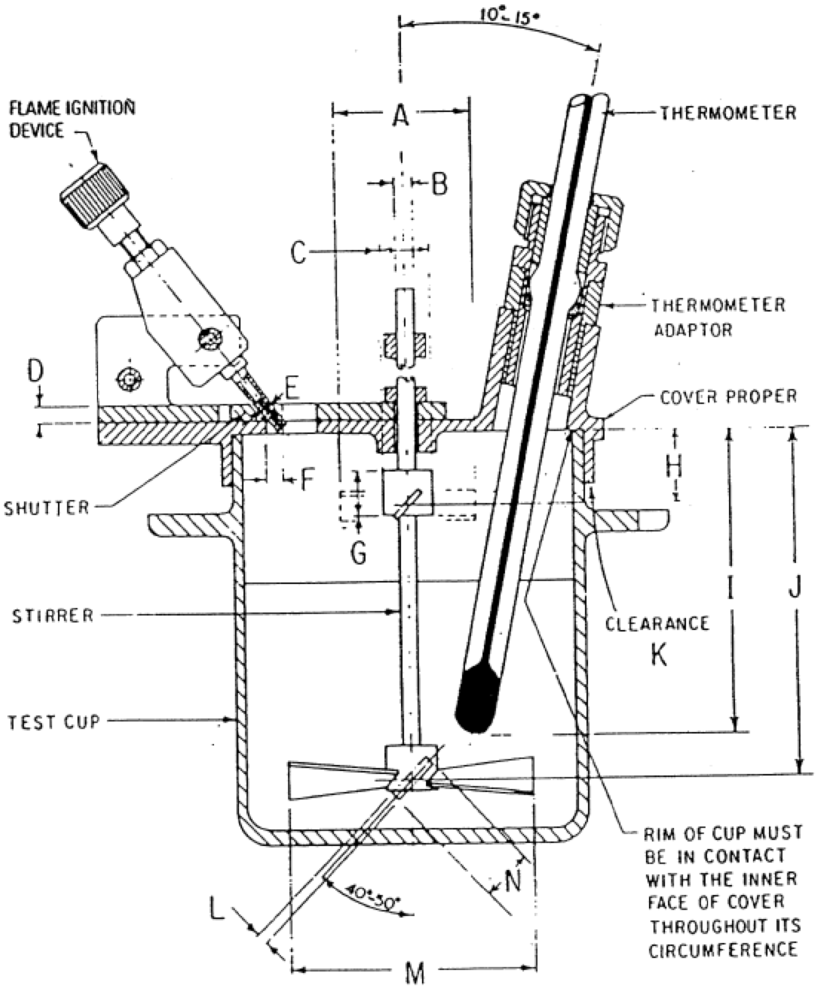


Figure B-1-1. ASTM D93-97 Pensky-Martens closed cup test apparatus for the flash point of fluids [7].

The cup has a marker to fill the cup with a fixed volume of fluid. The fluid is heated to a temperature below the flash point and a pilot flame is applied at a temperature reading that is a multiple of 5 ^{o}C.

The flash points of the selected engine compartment fluids were measured by FM Global using this Test Method [11].

7. ASTM E 659-78 STANDARD TEST METHOD FOR THE AUTOIGNITION OF FLUIDS

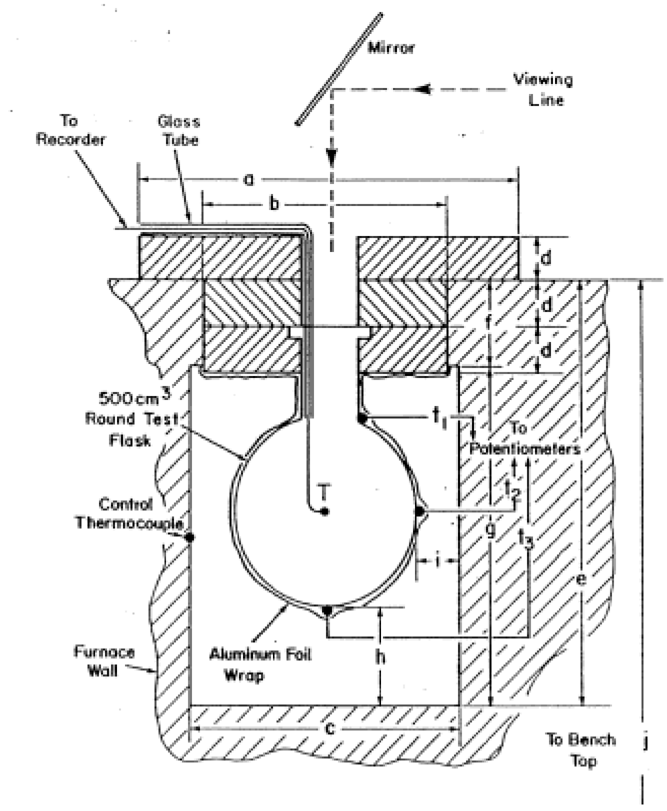


Figure B-1-2. ASTM E659-78 test apparatus for the measurement of autoignition temperature of fluids [7].

In the Test Method, 10-ml of fluid are injected into a uniformly heated 500-ml glass flask containing air at a predetermined temperature, measured by a thermocouple, located at the center of the flask, as shown in Fig. B-1-2 [7]. The contents of the flask are observed in a dark room for 10 minutes following the insertion of the sample or until autoignition occurs. Autoignition is evidenced by the sudden appearance of a flame inside the flask and by a sharp rise in the temperature of the gas mixture. The lowest internal flask temperature at which hot-flame ignition occurs for a series of prescribed sample volumes is taken to be the hot-flame autoignition temperature (**T_a**) of the fluid in air at atmospheric pressure. This Standard Test Method was used by UEC to measure the autoignition temperatures of the selected engine compartment fluids [11].

8. TEST METHOD FOR HOT SURFACE IGNITION

This Test Method was developed by GM to quantify the hot surface ignition temperature for selected engine compartment fluids [9]. In this Test Method, crucibles and hemispheres were cast from gray iron using green sand molds. The thickness of both walls of crucibles and the hemispheres was 13-mm (0.5-in). The crucibles were 38-mm (1.5-in) deep with outside and inside diameters of 178-mm (7-in) and 152-mm (6-in) respectively. The outside and inside diameters of the hemispheres were also 178-mm (7-in) and 152-mm (6-in) respectively with radius of 89-mm (3.5-in).

Each crucible was heated by an electric 220 V hot plate. Electric power to the crucible was supplied by a 220-V variable transformer. The inside surface temperature of the crucible was measured by a 24 gage K-type thermocouple spot welded to the center of the upper surface of the bottom of each crucible. The outer wall of the crucible was wrapped with a ceramic fiber insulating material, which in turn was wrapped with aluminum tape to help maintain a constant and uniform temperature on the upper surface of the bottom of the crucible. The temperature was monitored continuously and the output power from the transformer was adjusted manually to control the temperature.

The hemisphere was heated at the bottom by a Meeker burner using a welding grade mixture of methane, acetylene, and propylene. The hemisphere was supported by a ring attached to the Meeker burner. The height of the ring was adjusted so that the burner surface was about 13-mm (0.5-in) higher than the lip of the hemisphere. A 30 gage carbon steel trough, located about 25-mm (1-in) below the lip of the hemisphere, was used to collect the fluid that ran off the hemisphere. For the surface temperature measurements, a 24-gage K-type thermocouple was spot-welded to the apex of the hemisphere.

In the tests where crucibles were used, heat was turned on until the target temperature was achieved and was constant to ± 1 ^{o}C for a period of 3 to 5 minutes. At this time 25 ml of the fluid sample were poured directly onto the center of the crucible (where thermocouple was located) in 2 to 3 seconds. Measurements were made for air temperature, dew point, and barometric pressure. Ignition of the fluid was defined in terms of the generation and spontaneous ignition of the fluid vapors within five-minute interval after the fluid was poured into the crucible. The initial temperature and time for the ignition of the fluid vapors were recorded. Five or more replicate tests were performed at each temperature to determine the reproducibility of the data.

After each test, the inner walls and the bottom of the crucible were cleaned. The thermocouples were detached and the crucibles were placed in a muffle furnace maintained at 600 ^{o}C for approximately 60 minutes until residual fluid had charred. The crucibles were removed from the muffle furnace and allowed to cool. Char was removed by sand blasting using garnet. A new thermocouple was spot welded at the center of the bottom of the crucible.

In the tests with hemispheres, the Meeker burner was placed under the hemisphere and the temperature at the apex of the hemisphere was monitored continuously. When the temperature was 20 to 25 ^{o}C higher than the target temperature, gas supply to the Meeker burner was turned off and the hemisphere allowed to cool. When the target temperature was reached, 25 ml of the fluid sample were poured directly onto the apex of the hemisphere over a period of a few seconds. As the fluid was poured, it ran down the sides of the hemisphere into the trough. Ignition was defined as the spontaneous ignition of the fluid vapors as it was being poured onto the hemisphere or the residue of the fluid was vaporizing and generating smoke. The initial temperature and time were recorded at the ignition of the fluid vapors. Five or more replicate tests were performed at each temperature to determine the reproducibility of the data.

In some tests, a fan was used to produce airflow over the hemisphere. The fan was placed about 1.5-m (5-ft) from the hemisphere. The height and angle of the fan were adjusted so that the direction of the airflow was horizontal and impinged directly onto the hemisphere. The airflow rate was adjusted by the fan speed and the rate measured by an anemometer. In these tests, the fluid was poured onto the hemisphere slightly upwind of the apex to ensure that the fluid did not run down the leeward side of the hemisphere.

After each test, the fluid was removed from the trough. The hemisphere was cleaned by igniting the Meeker burner and heating the hemisphere until the temperature of the thermocouple at the apex was maintained at > 600 ^{o}C for a few minutes. This was sufficient to vaporize and oxidize residual fluid film on the outer surface of the hemisphere.

9. ASTM D2890-92 STANDARD TEST METHOD FOR CALCULATION OF LIQUID HEAT CAPACITY OF PETROLEUM DISTILLATE FUELS

For the calculation of the heat capacity of fluids, temperatures are used for 10, 30, 50, 70, and 90% volume percent distilled as measured by the ASTM D86 Test Method and the API gravity determined by the D287 Test Method or a method of equivalent accuracy are used in the following relationship [7]:

$$\mathbf{c_p = [0.6811 - 0.308G + (0.000815 - 0.000306G)/T](0.055K + 35)} \qquad \text{(B-1-1)}$$

where $\mathbf{c_p}$ is the heat capacity in BTU/lb-^{o}F; **G** is the specific gravity (calculated from Eq. B-3-1 Appendix B-3); **T** is the temperature in ^{o}F and **K** is the Watson characterization factor, which is calculated from the **API** gravity and the mean average boiling point.

In the GM sponsored studies [8], distillation data measured according to the ASTM D2887 Standard Test Method were used. The average mean boiling point (**BP_{avg}**) was calculated using the following equation [8]:

$$\mathbf{BP_{avg}} = \sum \mathbf{I_i} \ \mathbf{x} \ \mathbf{BP_i} \, / \sum \mathbf{I_i} \tag{B-1-2}$$

where **I_i** is the total ion current for chromatographic segment **i**, and **BP_i** is the boiling point of the hydrocarbon eluting in chromatographic segment **i**.

10. ASTM E 1269-95 STANDARD TEST METHOD FOR DETERMINING SPECIFIC HEAT CAPACITY BY DIFFERENTIAL SCANNING CALORIMETRY

The heat capacity is determined by heating the sample in a Differential Scanning Calorimeter (DSC) at a controlled rate through the region of interest [7]. The difference in heat flow into the sample and a reference material or blank due to energy changes is measured continuously and used in the calculation of the heat capacity. The occurrence of chemical changes or mass loss on heating during the measurement may invalidate the test. Thus, the temperature range and sample holders are chosen carefully to avoid the errors.

In the GM sponsored studies, a Modulated Differential Scanning Calorimeter (MDSC) was used for the measurement of energy changes [10]. In the tests, a hermitical sealed aluminum pan with pinhole of 0.8-mm in diameter was used as fluid sample container to eliminate errors due to vaporization in the pre-boiling region (other information is given in Section 5 of this Appendix). In the tests, indium and tin were used to calibrate the MDSC for temperature and sapphire for the heat capacity calibration.

11. ASTM E 681-98 TEST METHOD FOR THE LOWER AND UPPER LIMITS OF FLAMMABILITY OF FLUIDS

This Test Method uses the apparatus shown in Fig. B-1-3. It consists of a glass test vessel about 5 liters in volume, an insulated chamber equipped with a source of controlled air temperature, an ignition device with an appropriate power supply, a magnetic stirrer, and a cover equipped with the necessary operating connections and components.

The vessel is heated to desired temperature. After a period of equilibration, the vessel is evacuated, and pressure inside the vessel is measured. A measured volume of the fluid is introduced into the vessel by a hypodermic syringe. The stirring mechanism is activated to agitate the fluid and produce a large surface area for evaporation. After all the fluid has evaporated, pressure of the fluid vapor is measured. Air is then introduced until the pressure in the vessel is atmospheric, which is also measured. The fuel concentration is calculated from the ratios of the pressures of the fluid vapor and its mixture with air.

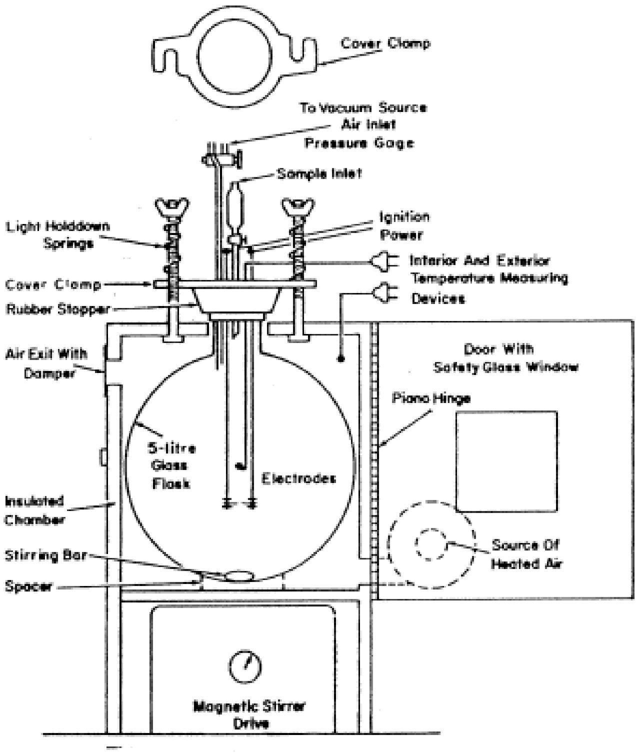


Figure B-1-3. ASTM E 681-98 test apparatus for the measurement of lower and upper flammability limits for fluids [7].

The high-energy source is activated for one second and flame propagation is observed in the test vessel. Fluid sample volume is varied to find the minimum sample volume L_1 that gives flame propagation[4] and the maximum sample volume L_2 below L_1 that does not give flame propagation. The difference between L_1 and L_2 is a measure of the variability of the procedure for the sample being studied. In a similar fashion, the highest fluid sample volume U_1 is determined for flame propagation and the least volume U_2 above U_1 that will not propagate a flame. The lower flammability limit (**LFL**) and the upper flammability limit (**UFL**) are then expressed as $(L_1+L_2)/2$ and $(U_1+U_2)/2$ respectively.

The Test Method is limited to an initial pressure of 101 kPa (1 atm) or less with a practical lower pressure limit of approximately 13.3 kPa (100 –mm Hg). The maximum operating temperature of this equipment is approximately 150 ^{o}C (302 ^{o}F), although tests can be

---

[4] Propagation of flame is defined in the test as the upward and outward movement of the flame front from the ignition source to the vessel walls or at least to within 13-mm (0.5-in) of the wall, which is determined by visual observations [7]. By outward, it is meant a flame front that has a horizontal component to the movement away from the ignition source [7].

performed up to 280 °C (536 °F). The **LFL** and **UFL** values for the engine compartment fluids were measured by Chilworth [11].

12. ASTM D240-92 TEST METHOD FOR THE HEAT OF COMPLETE COMBUSTION OF FLUIDS

The Test Method is used to measure gross heat of complete combustion, defined as the quantity of energy released when a unit mass of fuel is burned in a constant volume enclosure, with products being gaseous, other than water that is condensed to the liquid state [7]. The sample is weighed and then burned in an oxygen bomb calorimeter under controlled environment. The calorimeter has an internal volume of 350 ml, is completely enclosed within a stirred water jacket with sides, top, and bottom approximately 10-mm from the jacket wall. The controlled environment consists of 100 % oxygen at 3.0-Mpa (30 atmospheres) at room temperature. The mass of the fluid sample used is equivalent to 0.9 to 1.1 g of benzoic acid. The gross heat of complete combustion is computed from the temperature before, during, and after combustion with proper allowance for the thermo-chemical and heat transfer corrections.

The measured gross heat of complete combustion is used to determine the net heat of complete combustion defined as the quantity of energy released when a unit mass of fuel is burned at constant pressure, with all the products, including water, being gaseous[5]. Maxwell [24] has listed both gross and net heat of complete combustion for hydrocarbons, alcohols, glycols and glycerols, ethers, aldehydes, and ketones. Maxwell's data show that the net heat of complete combustion $\approx$ 0.9274 x gross heat of complete combustion with a standard deviation of 0.0438.

The gross heat of complete combustion was measured by FM Global using this Standard Test Method [11].

13. ASTM E2058 STANDARD TEST METHOD FOR THE MEASUREMENT OF SYNTHETIC POLYMER FLAMMABILITY USING A FIRE PROPAGATION APPARATUS (FPA)

The Test Apparatus is shown in Fig. B-1-4 [7]. This Standard Test Method was modified for the quantification of the fire properties of the engine compartment fluids. The engine compartment fluids were burned in a wick-like configuration to eliminate preferential distillation and early

---

[5] If the percentage of hydrogen atoms in the sample is known: net heat of complete combustion in MJ/kg = gross heat of complete combustion in MJ/kg – 0.2122 x mass percent of hydrogen atoms, where heats of combustion are in MJ/kg [7]. If the percentage of hydrogen atoms in aviation gasoline and turbine fuel samples is not known: net heat complete of complete combustion in MJ/kg = 10. 025 + (0.7195) x gross heat of combustion in MJ/kg [7].

combustion of low boiling point components. Furthermore, a much longer steady state burning period was available in the wick-like configuration that enhanced the accuracy of the fire property quantifications. The wick-like configuration consisted of a burlap cloth cylinder with a diameter of about 70-mm (2.6-in) and a height of about 50-mm (2-in). The burlap cloth was 50-mm (2-in) wide, 1.8-m (70-in) long and 1.5-mm (0.06-in) thick. It was washed with distilled water and dried before using it as a wick. The burlap wick was placed tightly inside a Pyrex dish that was 70-mm (2.6-in) in diameter and 50-mm (2-in) in height as shown in Fig. B-1-5. Each fluid was burned in a freshly washed and dried burlap cloth cylinder. The wick cylinder was discarded after every test.

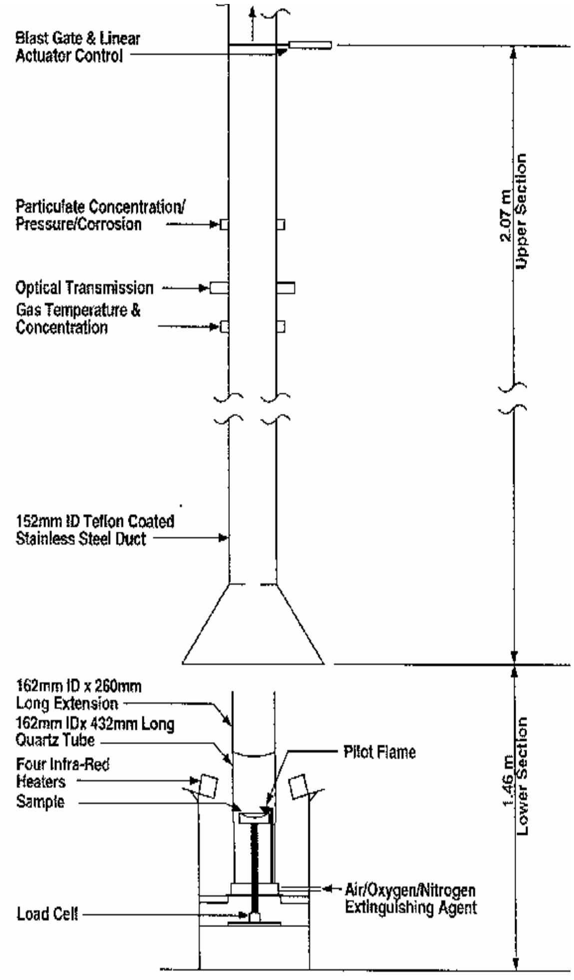


Figure B-1-4. The ASTM E-2058 Fire Propagation Apparatus [7].

In each test, the washed and dried burlap-cloth-wick cylinder in the Pyrex dish was soaked with 100 ml of the fluid by pouring it slowly on top of the cylinder such that the burlap-cloth-cylinder was soaked as uniformly as possible and there was no run off. A pipette was used to measure the fluid volume. The weights of the soaked and un-soaked burlap-cloth-wick cylinder in the Pyrex dish were measured and the weight of the fluid was calculated from the difference. The density each fluid was calculated from its weight and volume.

The fluid-soaked burlap cloth wick in the Pyrex dish was placed in the ASTM E2058 Apparatus at the location marked sample. The quartz tube was placed around the sample, inlet airflow and sampling duct exhaust flows were turned on, and a match was used to ignite the fluid soaked burlap-cloth-wick. No external heat flux was used in the tests. The fluids burned for a minimum of 300 seconds at the steady state, which was a sufficient time for measurements.

The fluid-soaked wick was burned under well-ventilated conditions (volumetric flow rate of 2.9 x 10^{-3} m^3/s). In each test, measurements were made for the release rates of vapors and heat, and generation rates of products. Heptane and methanol were used as reference fluids.

Figure B-1-5. Fluid soaked burlap cloth cylindrical wick inside a Pyrex dish.

APPENDIX B-2

THERMOPHYSICAL AND FIRE PROPERTY DATA FROM THE LITERATURE AND THEIR RELATIONSHIPS FOR FLUIDS

(References in Chapter II)

1. FLUID FLAMMABILITY

Ignition process is a vapor-phase combustion reaction with the evolution of heat and emission of light that may or may not be visible to the naked eye [4]. The ease with which vapors can be produced by heating a fluid is known as its volatility[1]. A fluid is considered highly volatile if its vapor pressure at a given temperature is high (i.e. $\mathbf{T_b}$ at a given pressure is low). Figure B-2-1 shows a relationship between the vapor pressure ($\mathbf{P_v}$) and the fluid temperature. The fluid vapor pressure increases with increase in the fluid temperature. At fluid temperature $\mathbf{T_L}$, a lean limit mixture is formed which is defined as the *lean limit of flammability or lower flammability limit (***LFL**)[2] [3]. $\mathbf{T_L}$ is related to the flash point ($\mathbf{T_{flash}}$) of the fluid. With further increase in the fluid temperature, the fluid reaches the fire point, $\mathbf{T_{fire}}$, where fluid vapor-air mixture ignites if a pilot flame is present. In the absence of a pilot flame, the fluid temperature continues to increase reaching the autoignition temperature ($\mathbf{T_a}$ or **AIT**) and the fluid vapor-air mixture ignites without a pilot flame. For the fluid temperature > $\mathbf{T_L}$, the fluid vapor-air mixture remains flammable until the *rich limit of flammability* or the *upper flammability limit (***UFL**)[3] is reached, beyond which the mixture becomes non-flammable due to highly fuel rich conditions [3].

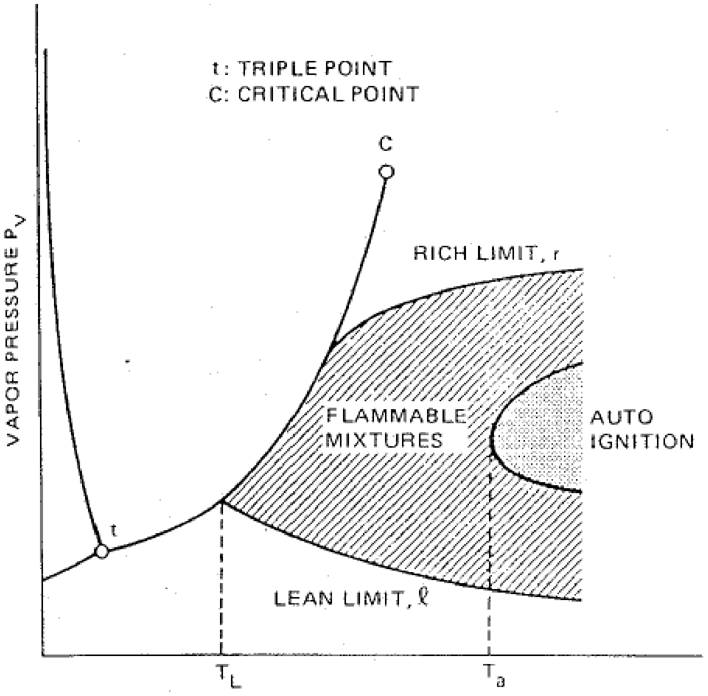


Figure B-2-1. Relationship between the vapor pressure and temperature for a fluid. Figure is taken from Ref. 3.

---

[1] The volatility (distillation) characteristics of fluids often have an important effect on their safety and performance, especially for fuels and solvents, for example creation of potentially explosive vapors. It is also important in affecting starting, warm-up and tendency to vapor lock at high engine operating temperatures and/or at high altitude and formation of solid combustion deposits.

[2] **LFL** is defined as the lowest volume percent of the fluid vapor in the mixture with air that will barely support flame spread away from the pilot flame [2,3].

The **LFL** value of a fluid depends on the temperature of the environment, as indicated by the following relationship [4]:

$$\mathbf{LFL_T / LFL_{25} = 1 - (0.75 / LFL_{25} \Delta H_T)(T - 25^o)} \qquad \text{(B-2-1)}$$

where $\mathbf{LFL_T}$ and $\mathbf{LFL_{25}}$ are the lower flammability limits in volume percents at temperatures **T** and 25 ^{o}C respectively, $\mathbf{\Delta H_T}$ is the net heat of complete combustion (kcal/mol) and 0.75 is essentially a molar heat capacity constant x 100.

If the heat release $\mathbf{LFL_{25}}$ x $\mathbf{\Delta H_T/100}$ can be assumed to be constant, as it is for many hydrocarbons, the **LFL** value would decrease linearly with increasing temperature and converge at some limit temperature which corresponds to zero concentration (**LFL** = 0) [4]. For hydrocarbons, this limit temperature is about 1300 ^{o}C [4]. An ideal value of $\mathbf{T_{flash}}$ for a fluid can be calculated from Eq. B-2-1 using its $\mathbf{LFL_{25}}$ value and its vapor pressure-temperature relationship [4].

An expression similar to Eq. B-2-1 also exists for the **UFL** values of fluids at various temperatures [4]. However, the relationship is somewhat unreliable because of the presence of cool flames, soot formation, or other incomplete combustion modes associated with fuel-rich flames [4].

2. Flash Point

The measured $\mathbf{P_V}$ and $\mathbf{T_{flash}}$ values for variety of fluids and gases suggest the following trends [4].

2.1 Saturated hydrocarbons

1) Normal alkanes with more than eight carbon atoms (above octane) do not form flammable vapor-air mixtures below 30 ^{o}C and atmospheric pressure;

2) Chain branching increases the volatility and decreases the $\mathbf{T_{flash}}$ value;

3) $\mathbf{T_{flash}}$ values of paraffin series increase with increasing value of the molecular weight (**M)** of the fluid, whereas the corresponding vapor pressures and **LFL** vary inversely. Following relationships have been developed for predicting the $\mathbf{T_{flash}}$ values in ^{o}C for normal paraffins [4]:

---

[3] **UFL** is defined as the highest volume percent of the fluid vapor in the mixture with air that will barely support flame spread away from the pilot flame [2,3].

$$
\begin{aligned}
(\mathbf{T_{flash}} + \mathbf{273.7})^2 &= \mathbf{10{,}410\,n} \\
(\mathbf{T_{flash}} + \mathbf{273.7})^2 &= \mathbf{741.7 / P_V} \\
(\mathbf{T_{flash}} + \mathbf{273.7})^2 &= \mathbf{77{,}291\,(1 / LFL_{25}) - 3{,}365}
\end{aligned}
\qquad \text{(B-2-2)}
$$

where **n** is the number of carbon atoms.

2.2 Other Liquids and Gases

1) As with paraffins, $\mathbf{T_{flash}}$ values for each homologues series generally increase with increasing number of carbon atoms and decrease with chain branching;

2) Correlations with carbon atoms and heats of combustion are practically linear for certain normal alkyl compounds (paraffins, cyclohexanes, ketones, alcohols, acetates) and alkyl benzenes but not for their isomers;

3) Functional groups have a large and varied effect on the $\mathbf{T_{flash}}$ values, such as

For Butane	$\mathbf{T_{flash}}$ **(°C)**	**For Benzene**	$\mathbf{T_{flash}}$ **(°C)**
C_4H_{10}	-74	C_6H_6	-11
$C_4H_9NH_2$	-12	C_6H_5Cl	29
C_4H_9Cl	-9	C_6H_5Br	51
C_3H_7CHO	-7	$C_6H_4Cl_2$	66
C_4H_9SH	2	$C_6H_5NH_2$	70
C_4H_9Br	18	C_6H_5OH	79
C_4H_9OH	29	$C_6H_5NO_2$	88
C_3H_7COOH	72		

Effects of any functional group on $\mathbf{T_{flash}}$ values depend on the changes produced in both volatility and on **LFL** values. In general, the $\mathbf{T_{flash}}$ values of such hydrocarbon derivatives are noticeably greater compared to their parent hydrocarbons.

2.3 Blends of Fluids

1) Predictions for the $\mathbf{T_{flash}}$ values are complex and depend on the deviations from ideal mixture laws. Anomalous behaviors occur with dissimilar molecular species, such as mixture of hydrocarbons and halogenated, oxygenated, or nitrated hydrocarbon;

2) $\mathbf{T_{flash}}$ values for many solvent blends are often lower than expected because of polarity, hydrogen bonding, or solubility parameter differences;

3) $\mathbf{T_{flash}}$ values of the mixtures are affected strongly by the component that has the highest volatility. In cases where a highly volatile component is present in only small concentrations as an additive or contaminant, the $\mathbf{T_{flash}}$ values are subject to the evaporative history of the mixture. Depending on the evaporation period, the $\mathbf{T_{flash}}$ values may be overestimated when the volatile additive is nonflammable and underestimated when the additive is more flammable than the main fluid components.

2.4 Flammability Limit

The measured **LFL** and **UFL** values for variety of gases and fluids suggest the following trends [4].

2.4.1 Saturated Hydrocarbons and Derivates

1) For the lowest member of the paraffin series (methane), the **LFL** value is 5% and the **UFL** value is 15%;

2) For most homologues series (such as normal paraffins and their corresponding alcohols, aldehydes, amines and chlorides), **LFL** and **UFL** values decrease with increase in the **M** value and in the number of carbon atoms (**n**);

3) On a weight basis, the **LFL** values for most saturated hydrocarbons are about 45 ± 5 mg per liter of air at standard conditions (0^{o}C and 1 atmosphere), whereas the **UFL** values typically fall between 200 and 400 mg per liter, excluding methane;

4) Following correlations have been developed to predict the **LFL** and **UFL** values in volume percent:

$$\begin{aligned}
&\mathbf{LFL_{25} \cong 0.55\ C_{st};}\\
&\mathbf{UFL_{25} \cong 4.8\ C_{st}^{1/2};}\\
&\mathbf{1/LFL_{25} = 0.1347\ n + 0.04353;}\\
&\mathbf{1/UFL_{25} = 0.01337\ n + 0.05151;}\\
&\mathbf{LFL_T / LFL_{25} = 1 - 0.000721(T - 25^{o});}\\
&\mathbf{UFL_T / UFL_{25} = 1 + 0.000721(T - 25^{o})}
\end{aligned} \qquad \text{(B-2-3)}$$

where $\mathbf{C_{st}}$ is the concentration of the fluid in volume percent for stoichiometric combustion to CO_2 and H_2O. The correlations are reliable for the normal paraffins (n-alkanes) and many of their isomeric, cyclic, and substituted derivates. Corresponding correlations to predict $\mathbf{UFL_{25}}$ are less reliable.

2.4.2 Unsaturated Hydrocarbons, Aromatics, and Derivates

1) Main classes of unsaturated hydrocarbons are alkenes (olefins) and alkynes (acetylenes);

2) The **LFL** and **UFL** values decrease with increasing number of carbon atoms, similar to the alkanes series, but tend to be wider because of the higher upper limits;

3) Alkynes present a greater flammability hazard than alkenes because of their greater thermal instability and ability to form decomposition flames with or without air;

4) Aromatic hydrocarbons have flammability limits that are comparable to or narrower than the values for their paraffin homologues with the same number of carbon atoms.

2.4.3 Inorganics

1) Some inorganics, such as hydrogen and CO, have much wider flammability limits in ambient air than the saturated and unsaturated hydrocarbons, excluding those of high thermal instability such as acetylenes. The flammability range for H_2 is 4.0 to 75% and for CO it is 12.5 to 74% in air at 25 ^oC and atmospheric pressure;

2) Amongst the nitrogen containing inorganics, hydrazine has the widest flammability range (4.7 to 100%) in air and ammonia the narrowest (15 to 28%).

2.5 Ignition and Flammability Properties

Values of $\mathbf{T_{flash}}$, $\mathbf{T_L}$, $\mathbf{T_{fire}}$, $\mathbf{T_a}$ (**AIT**) and $\mathbf{T_b}$ for gases and fluids are interrelated. For example, the $\mathbf{T_{flash}}$ value is related to the $\mathbf{T_L}$ value for piloted ignition [3]. The definition of $\mathbf{T_{fire}}$ is very similar to the definition of $\mathbf{T_{flash}}$, except that at $\mathbf{T_{fire}}$ value, flame does not merely flash or cease but becomes self sustained and burning is continued. The definition of $\mathbf{T_a}$ (**AIT**) is similar to the definition of $\mathbf{T_{fire}}$, except that $\mathbf{T_a}$ value occurs at higher fluid temperature, where the fluid ignites by itself.

The values of $\mathbf{T_{flash}}$ and $\mathbf{T_b}$ for gases and liquids correlate since they are governed largely by the same phenomenon, i.e., volatility. Hot surface ignition is affected both by the chemical reactivity and by the volatility of the fluid [12]. In an enclosed volume, hot surface ignition temperature of a fluid is similar to the $\mathbf{T_a}$ value of the fluid [12]. This condition, however, is rare and generally, the hot surface ignition temperature is 200 ^oC above the $\mathbf{T_a}$ value of the fluid [12].

The **LFL** values of liquids and gases have been correlated with their heat of vaporization ($\mathbf{\Delta H_v}$), $\mathbf{T_{flash}}$, and $\mathbf{T_b}$ values, following the Clausius-Clapeyron relationship [3]:

$$\mathbf{\ln(1/LFL) \geq [\Delta H_v/(R/M)T_b][(T_b - T_{flash})/T_{flash}]} \qquad \text{(B-2-4)}$$

where **R** is the universal gas constant (8.314 J/mole-K). For many non-polar fluids, $\mathbf{\Delta H_v /(R/M)\, T_b}$ is approximately constant with an average value 10.18 (Trouton's Rule) [3]. In general, the **LFL** values measured in the experiments are less than the values calculated from Eq. 4 [3]. The reasons for this discrepancy is suggested to be due to [3]: 1) dependency of the relationship in Eq. 4 on the transient convective-diffusion process that plays a crucial role in determining the $\mathbf{T_{flash}}$ values, and 2) empirical nature of **LFL** with no quantitative knowledge of its dependency on the fundamental properties of the system. The Trouton's Rule provides a relationship to calculate the **M** values of the fluids from their $\mathbf{T_b}$ and $\mathbf{\Delta H_v}$ values [3]:

$$\mathbf{M \approx 10.18\, R(T_b / \Delta H_v) \;\approx 84.64 (T_b / \Delta H_v)} \qquad \text{(B-2-5)}$$

Data for variety of liquids and gases from Ref. 3 suggest that the value of the constant on the right hand of Eq. 5 is slightly higher (92.39 rather than 84.64).

Measurements for the retention times, $\mathbf{t_R}$, of the components in fluids by a gas chromatograph (GC)[4] also provides a methodology to calculate the **M** and $\mathbf{T_b}$ values of the fluids, using the following relationships [8]:

1) Molecular Weight (**M**):

$$\mathbf{M = 50.4041 + 3.4883\, t_R - 0.0115\, t_R^2 + 0.0007\, t_R^3} \;\; (5.57 \le \mathbf{t_R} < 57.35) \qquad \text{(B-2-6)}$$

$$\mathbf{M = 1948.3117 - 95.3008\, t_R + 1.6912\, t_R^2 - 0.0091\, t_R^3} \;\; (57.35 \le \mathbf{t_R} < 77.72) \qquad \text{(B-2-7)}$$

2) Boiling Point ($\mathbf{T_b}$):

$$\mathbf{T_b = -39.1444 + 12.2042 t_R - 0.1708 t_R^2} \;\; (5.57 \le \mathbf{t_R} < 12.67) \qquad \text{(B-2-8)}$$

$$\mathbf{T_b = 3.0369 + 6.7120 t_R} \;\; (12.67 \le \mathbf{t_R} < 67.20) \qquad \text{(B-2-9)}$$

$$\mathbf{T_b = -182.6782 + 11.9363 t_R - 0.0108 t_R^2 - 0.000038 t_R^3} \;\; (67.20 \le \mathbf{t_R} < 90) \qquad \text{(B-2-10)}$$

2.6 Combustion of Gases and Liquids

The ignition process is followed by the combustion process. The fluid vaporization and combustion continues as long as the heat continues to be transferred from the flame of the

---

[4] GC has also been used in ASTM standard test methods (such as ASTM D 2887-01 [7] for the simulation of fluid distillation and for the boiling point determination. For such an application, the GC is calibrated by fluid mixtures, such as n-alkanes (C_5 through C_{44}) and by a gravimetrically prepared mixture of paraffins, isoparaffins, aromatics, naphthenes and olefins (PIANO) [8].

burning fluid vapors and/or external heat sources and there is fluid to vaporize. The release rates of fluid vapors and heat and the generation rates of the combustion products satisfy the following relationships [5, 13, 14, 15, 18]:

$$\dot{\mathbf{m}}_{\mathbf{f}}'' = \dot{\mathbf{q}}_{\mathbf{n}}'' / \Delta\mathbf{Hv} \tag{B-2-11}$$

$$\dot{\mathbf{Q}}_{\mathbf{i}}'' = \Delta\mathbf{H}_{\mathbf{i}}\dot{\mathbf{m}}_{\mathbf{f}}'' \tag{B-2-12}$$

$$\dot{\mathbf{Q}}_{\mathbf{i}}'' = (\Delta\mathbf{H}_{\mathbf{i}} / \Delta\mathbf{H}_{\mathbf{v}})\dot{\mathbf{q}}_{\mathbf{n}}'' \tag{B-2-13}$$

$$\dot{\mathbf{G}}_{\mathbf{j}}'' = \mathbf{y}_{\mathbf{j}}\,\dot{\mathbf{m}}_{\mathbf{f}}'' \tag{B-2-14}$$

$$\dot{\mathbf{G}}_{\mathbf{j}}'' = (\mathbf{y}_{\mathbf{j}} / \Delta\mathbf{H}_{\mathbf{v}})\dot{\mathbf{q}}_{\mathbf{n}}'' \tag{B-2-15}$$

$$\dot{\mathbf{q}}_{\mathbf{n}}'' = \dot{\mathbf{q}}_{\mathbf{f}}'' + \dot{\mathbf{q}}_{\mathbf{e}}'' - \dot{\mathbf{q}}_{\mathbf{rr}}'' \tag{B-2-16}$$

$$\Delta\mathbf{H}_{\mathbf{v}} = \int_{\mathbf{T_0}}^{\mathbf{T_b}} \mathbf{c}_{\mathbf{p}}\mathbf{dT} + \mathbf{E}_{\mathbf{v}} \tag{B-2-17}$$

where $\dot{\mathbf{m}}_{\mathbf{f}}''$ is the mass release rate of fluid vapors (g/m^2-s); $\dot{\mathbf{q}}_{\mathbf{n}}''$ is the net heat flux (kW/m^2); $\Delta\mathbf{H}_{\mathbf{v}}$ is the heat of vaporization of the fluid (kJ/g); $\dot{\mathbf{Q}}_{\mathbf{i}}''$ is the heat release rate (kW/m^2); subscript **i** is the total, chemical, convective or radiative component of the heat release rate; $\Delta\mathbf{H}_{\mathbf{i}}$ is the net heat of complete combustion, chemical heat of combustion, convective heat of combustion, or radiative heat of combustion (kJ/g); $\dot{\mathbf{G}}_{\mathbf{j}}''$ is the release rate of product j (g/m^2-s); $\mathbf{y}_{\mathbf{j}}$ is the yield of product j (g of product/g of fluid vapors); $\dot{\mathbf{q}}_{\mathbf{f}}''$ is the flame heat flux (kW/m^2); $\dot{\mathbf{q}}_{\mathbf{e}}''$ is the external heat flux (kW/m^2); $\dot{\mathbf{q}}_{\mathbf{rr}}''$ is the surface re-radiation loss (kW/m^2); $\mathbf{T_0}$ is the ambient temperature (K); $\mathbf{T_b}$ is the boiling point (K), $\mathbf{c_p}$ is the heat capacity (kJ/g-K), and $\mathbf{E_v}$ is the vaporization energy of the fluid (kJ/g).

2.6.1 Large Pool Fires of Fluids

Pool fires of fluids have been investigated in many studies [5, 6, 13-19]. The release rates of fluid vapors, heat and products depend on the mode of heat transfer from the flame to the fluid, which is governed by the pool size. There are three modes of heat transfer from the flame: conduction, convection, and radiation [14-16]. Heat transfer by conduction, a major mode of heat transfer for the combustion of fluids in very small pool diameters (about 0.004-m to about 0.030-

m), is through the pool rim (the edge effect) and is associated with the condensed-phase transformation [14-16]. In this pool diameter range, release rate of fluid vapors decreases with increase in the pool diameter.

Heat transfer by convection, a major mode of heat transfer for pool fires with moderate pool diameters, in the range of about 0.030-m to 0.20-m, is driven by the flow movements induced in the surroundings [14-16]. It occurs at all stages, but is of particular importance at the early stages of fire growth, when flame is small and the radiative contribution is low. In this range, release rate of fluid vapors is almost independent of the pool diameter [14-16].

For pool diameter > 0.25-m, radiative heat transfer contribution increases with pool diameter [14-16]. For example, convective heat transfer from the flame to the pool surface decreases from about 54 to 5 % as pool diameter increases from about 0.15-m to 0.50-m. Release rate of fluid vapors increases rapidly with increase in the pool diameter in this range.

For pool diameters > 1-m, radiative heat transfer to the pool surface becomes the dominant mode of heat transfer in controlling the release rate of fluid vapors [14-16]. However, the radiative heat transfer to the pool surface is attenuated by the presence of cool, fuel-rich region near the pool surface[5]. The attenuation of the radiative heat transfer increases with pool diameter. Thus, for the pool diameter in the range of about 0.5-m to 3-m, release rate of fluid vapors reaches its limit and decreases for diameters beyond about 3-m [14-16].

2.6.1.1 Release Rates of Fluid Vapors and Heat in Large Pool Fires

Examples of the $\dot{\mathbf{m}}_{\mathbf{f}}''$ values measured in large pool fires of fluids [13,16-19] are listed in Table B-2-1. The $\mathbf{\Delta H_v}$ values of the fluids from the literature are also included in the table along with the estimated $\dot{\mathbf{q}}_{\mathbf{n}}''$ values from Eq. B-2-11. The estimated $\dot{\mathbf{q}}_{\mathbf{n}}''$ values are approximately constant with an average of 33 kW/m^2 and a standard deviation of 5 kW/m^2, suggesting that in large pool fires, $\dot{\mathbf{q}}_{\mathbf{n}}''$ values are weakly dependent on the generic nature of the fluids. Equations B-2-11, B-2-13 and B-2-15 suggest the following relationships for constant $\dot{\mathbf{q}}_{\mathbf{n}}''$ value (approximately equal to 33 kW/m^2) for large pool fires:

---

[5] This phenomenon is called radiative energy blockage [16].

$$\dot{\mathbf{m}}_{\mathbf{f}}'' \approx \mathbf{33/\Delta H_v} \approx \mathbf{33/(\Delta H_v} + \int_{\mathbf{T_0}}^{\mathbf{T_b}} \mathbf{c_p\, dT)} \tag{B-2-18}$$

Table B-2-1. Heat of Vaporization, Release Rate of Fluid Vapors, and Estimated Net Flame Heat Flux for the Combustion of Fluids in Large Pool Fires

Fluid	**ΔH_v (kJ/g)**	**d (m)**	**$\dot{m}_f''$ (g/m^2-s)**				**$\dot{q}_n''$ (kW/m^2)**
			[13]	[17]	[18]	[19]	
Heptane	0.493	1.6		81			40
		2.4		79			39
		1.2-10	75				37
Hexane	0.481	3		79			38
		0.75-10	77				37
Octane	0.550	1.0				69	38
Dodecane	0.770	0.94	36				28
Benzene	0.543	0.75-6.0	81		88		44
Toluene	0.513	1.0				68	35
		1.6		64			33
Xylene	0.503	1.22	67				34
		5.4		60	86		38
		22.3		62			31
Kerosine	0.446	30-50		65			29
Gasoline	0.500	3		60			30
		5.4		70			35
		22.3		62			31
JP-4	0.500	1.0-5.3	67				34
JP-5	0.500	0.60-17	75				38
Transformer fluids	0.871	2.37	27				24
Methanol	0.960	1.2-2.4	25			24	27
Ethanol	1.00	5.0				30	30
Acetone	0.632	1.52	38				24
Toluene diisocyanate	0.870	0.3				23	20
		1.0				34	30
		1.5				39	34
		2.0				33	29
Adiponitrile	1.00	1.0				36	36
		1.5				35	35
		2.0				30	30
Acetonitrile	0.571	0.7				63	36
		1.0				58	33
						Average	33

Fluid	**ΔH_v (kJ/g)**	**d (m)**	**$\dot{m}_f''$ (g/m^2-s)**				**$\dot{q}_n''$ (kW/m^2)**
			[13]	[17]	[18]	[19]	
Standard Deviation							5

$$\dot{Q}_i'' \approx 33(\Delta H_i / \Delta H_v) \tag{B-2-19}$$

$$\dot{G}_j'' \approx 33\,(y_j / \Delta H_v) \tag{B-2-20}$$

The $\dot{Q}_i''$ and $\dot{G}_j''$ values can be calculated from Eqs. B-2-19 and B-2-20, using data reported in the literature for the thermophysical and fire properties of fluids to obtain the $\Delta H_i/\Delta H_v$ and $y_j/\Delta H_v$ values [13]. The ratio $\Delta H_i/\Delta H_v$ is defined as the Thermal Response Parameter (**HRP**) of a fluid [13]. Selected values of **HRP** calculated from the literature data are listed in Table B-2-2 along with $\dot{Q}_i''$ values calculated from Eq. B-2-19. These $\dot{Q}_i''$ values are the maximum possible rates expected for these fluids in large-scale pool fires, however, further increase in the pool diameter for very large pool fires, $\dot{Q}_i''$ values decrease due to radiative energy blockage and combustion inefficiency [14, 16, 17, 20].

The dependency of pool fires on the thermophysical and fire properties can be enumerated further, by substituting the relationship for ΔH_v from Eq. B-2-5 into Eqs. B-2-18, B-2-19, and B-2-20 and rearranging:

$$1/\dot{m}_f'' \approx 2.56\,(T_b / M) + 0.030\int_{T_0}^{T_b} c_p\, dT \tag{B-2-21}$$

$$1/\dot{Q}_i'' \approx (1/\Delta H_i)[2.56(T_b\ / M) + 0.030\int_{T_0}^{T_b} c_p\, dT] \tag{B-2-22}$$

$$1/\dot{G}_j'' \approx (1/y_j)[2.56(T_b / M) + 0.030\int_{T_0}^{T_b} c_p\, dT] \tag{B-2-23}$$

These relationships suggest that in large pool fires where $\dot{q}_n''$ is approximately constant (≈ 33 kW/m^2), the release rates of fluid vapors and heat and generation rates of products are governed by the **M**, T_b, c_p, $\Delta H_i/\Delta H_v$ and $y_j/\Delta H_v$ values of the fluids and the ambient temperature.

2.6.2 Heats of Combustion and Yields of CO and Smoke for Gases and Liquids

For variety of gases and liquids, data are available in the literature for heats of combustion ($\mathbf{\Delta H_{ch}}$, net heat of complete combustion, $\mathbf{\Delta H_{T}}$, radiative heat of combustion, $\mathbf{\Delta H_{rad}}$, and convective heat of combustion, $\mathbf{\Delta H_{con}}$) and yields of CO and smoke ($\mathbf{y_{co}}$ and $\mathbf{y_{smoke}}$) [13]. These values are listed in Tables B-2-3 to B-2-8. From these data, following correlations have been developed between the $\mathbf{\Delta H_i}$ and **M** values of the fluids [13]:

$$\mathbf{\Delta H_i = h_i \pm m_i / M} \qquad \text{(B-2-24)}$$

$$\mathbf{y_j = a_j \pm b_j / M} \qquad \text{(B-2-25)}$$

where $\mathbf{h_i}$ is the mass coefficient for the heat of combustion (kJ/g), $\mathbf{m_i}$ is the molar coefficient for the heat of combustion (kJ/mole), $\mathbf{a_j}$ is the mass coefficient for the product yield (g/g) and $\mathbf{b_j}$ is molar coefficient for the product yield (g/mole).

Table B-2-2. Composition, Molecular Weight, Heat Release Parameter and Estimated Heat Release Rate for Large Pool Fires of Fluids

Fluid	Composition	M (g/mole)	HRP (kJ/kJ)	$\dot{Q}''_{ch}$ (kW/m^2)^b
Gasoline-1	a	a	85	2805
Hexane-2	C_6H_{14}	86	83	2739
Heptane-3	C_7H_{16}	100	75	2475
Octane-4	C_8H_{18}	114	68	2244
Nonane	C_9H_{20}	128	64	2112
Decane-5	$C_{10}H_{22}$	142	59	1947
Undecane	$C_{11}H_{24}$	156	55	1815
Dodecane-6	$C_{12}H_{26}$	170	52	1716
Tridecane	$C_{13}H_{28}$	184	50	1650
Kerosine-7	$C_{14}H_{30}$	198	47	1551
Hexadecane	$C_{16}H_{34}$	226	44	1452
Mineral oil-8	a	466	72	2376
Motor oil	a	a	62	2046
Corn Oil-9	a	a	54	1782
Benzene-10	C_6H_6	78	75	2475
Toluene	C_7H_8	92	82	2706
Xylene	C_8H_{10}	106	67	2211

Methanol-11	CH_4O	32	19	627
Ethanol-12	C_2H_6O	46	33	1089
Propanol	C_3H_8O	60	46	1518
Butanol	$C_4H_{10}O$	74	58	1914

a: these fluids are complex mixtures with variable chemical compositions, manufacturer, origin, and others; **b**: estimated from Eq. 13, Chapter III.

The values of $\mathbf{h_i}$, $\mathbf{m_i}$, $\mathbf{a_j}$ and $\mathbf{b_j}$ have been published in the literature [13]. The values of the parameters depend on the chemical structure of the fluids; values of $\mathbf{m_i}$ and $\mathbf{b_j}$ become negative if oxygen, nitrogen, and sulfur atoms are present in the chemical structures of the fluids. For fluids with high **M** values, $\mathbf{\Delta H_i}$ and $\mathbf{y_j}$ values become approximately equal to $\mathbf{h_{ch}}$ and $\mathbf{a_j}$ respectively and do not vary with further increase in **M** value.

Table B-2-3. Thermophysical Properties of Saturated Aliphatic Hydrocarbons

Fluid	Composition		M (g/mole)	Sp gr	T_b (^{o}C)	s (g/g)	C_{st} (%)	T_{flash} (^{o}C)	T_a (^{o}C)	c_P (kJ/kg-K)		LFL (%)	UFL (%)
	C	H								Liquid	Vapor		
Ethane	2	6	30	1.04	-89	16.0	5.65	-135	515		1.75	3.0	12.4
Propane	3	8	44	1.52	-42	15.6	4.02	-104	450		1.65	2.1	9.5
Butane	4	10	58	2.01	-0.5	15.4	3.12	-74	370		1.68	1.8	8.4
Pentane	5	12	72	2.49	36	15.3	2.55	-49	260		1.67	1.4	7.8
Hexane	6	14	86	2.98	69	15.2	2.16	-23	225	2.27	1.66	1.2	7.4
Heptane	7	16	100	3.46	98	15.1	1.87	-3	225	2.25	1.66	1.1	6.7
Octane	8	18	114	3.94	126	15.1	1.65	14	220	2.23	1.66	0.95	6.5
Nonane	9	20	128	4.43	151	15.0	1.47	31	205	2.22	1.65	0.85	
Decane	10	22	142	4.91	174	15.0	1.33	46	210	2.22	1.65	0.75	5.6
Undecane	11	24	156			15.0				2.21	1.65		
Dodecane	12	26	170	5.88	215	14.9	1.12	74	204	2.21	1.65	0.60	
Tridecane	13	28	184			14.9				2.21	1.65		
Tetradecane	14	30	198	6.85	253	14.9	0.97	107	200	2.21	1.65	0.50	
Hexadecane	16	34	226	7.82	287	14.9	0.85	126	205	2.22	1.65	0.43	
Methylbutane	5	12	72	2.49	28	15.3	2.55	<-50	420	2.29	1.66	1.4	7.6
Dimethyl-butane	6	14	86	3.0	50	15.2	2.16	-48	425	2.19	1.63	1.2	7.0
Methyl-pentane	6	14	86	3.0	60	15.2	2.16		306	2.22	1.66	1.2	7.0
Dimethyl-pentane	7	16	100	3.5	90	15.1	1.87		335	2.21	1.66	1.1	6.8
Isooctane	8	18	114	3.9	99	15.1	1.65	-12	415			0.95	6.0
Ethylhexane	8	18	114			15.1							
Dimethyl-hexane	8	18	114			15.1					1.65		
Cyclopentane	5	10	70	2.42	49	14.7	2.72		380	1.76	1.08	1.5	
Methylcyclopentane	6	12	84			14.7				1.89	1.31		
Cyclohexane	6	12	84	2.91	81	14.7	2.27	-20	245	1.81	1.27	1.3	7.8
Methylcyclohexane	7	14	98	3.39	101	14.7	1.96	-4	250	1.89	1.38	1.1	6.7
Ethylcyclohexane	8	16	112	1.71	132	14.7	1.71	35	280	1.87	1.42	0.95	6.6
Dimethylcyclo hexane	8	16	112			14.7				1.88	1.40		
Cyclooctane	8	16	112			14.7							

Table B-2-4. Combustion Properties of Saturated Aliphatic Hydrocarbons

Fluid	C	H	M (g/mole)	ΔH_v	ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}	y_{co2}	y_{co}	y_{sm}
				kJ/g					g/g		
Normal Alkanes											
Ethane	2	6	30	0.489	47.1	45.7	34.1	11.6	2.82	0.001	0.013
Propane	3	8	44	0.426	46.0	43.7	31.2	12.5	2.85	0.005	0.024
Butane	4	10	58	0.386	45.4	42.6	29.6	13.0	2.81	0.007	0.029
Pentane	5	12	72	0.365	45.0	42.0	28.7	13.3	2.85	0.008	0.033
Hexane	6	14	86	0.365	44.8	41.5	28.1	13.4	2.83	0.009	0.035
Heptane	7	16	100	0.365	44.6	41.2	27.6	13.6	2.83	0.010	0.037
Octane	8	18	114	0.298	44.5	41.0	27.3	13.7	2.84	0.010	0.038
Nonane	9	20	128	0.288	44.4	40.8	27.0	13.8	2.84	0.011	0.039
Decane	10	22	142	0.360	44.3	40.7	26.8	13.9	2.84	0.011	0.040
Undecane	11	24	156	0.308	44.3	40.5	26.6	13.9	2.82	0.011	0.040
Dodecane	12	26	170	0.293	44.2	40.4	26.4	14.0	2.84	0.011	0.041
Tridecane	13	28	184	0.295	44.2	40.3	26.3	14.0	2.83	0.012	0.041
Tetradecane	14	30	198	0.291	44.1	40.3	26.2	14.1	2.83	0.012	0.042
Hexadecane	16	34	226	0.285	44.1	40.1	26.0	14.1	2.81	0.012	0.042
Substituted Alkanes											
Methyl butane	5	12	72	0.376	45.0	40.9	27.2	13.7	2.77	0.012	0.042
Dimethyl butane	6	14	86	0.354	44.8	40.3	26.3	14.0	2.75	0.014	0.046
Methyl pentane	6	14	86	0.373	44.8	40.3	26.3	14.0	2.75	0.014	0.046
Dimethyl pentane	7	16	100	0.339	44.6	39.9	25.7	14.2	2.74	0.015	0.049
Methyl hexane	7	16	100	0.360	44.6	39.9	25.7	14.2	2.76	0.015	0.049
Isooctane	8	18	114	0.298	44.5	39.6	25.3	14.3	2.74	0.016	0.052
Methylethyl pentane	8	18	114	0.331	44.5	39.6	25.3	14.3	2.74	0.016	0.052
Ethylhexane	8	18	114	0.346	44.5	39.6	25.3	14.3	2.74	0.016	0.052
Dimethyl hexane	8	18	114	0.328	44.5	39.6	25.3	14.3	2.72	0.016	0.052
Methyl heptane	8	18	114	0.346	44.5	39.6	25.3	14.3	2.74	0.016	0.052
Cyclopentane	5	10	70	0.443	44.3	39.2	24.1	15.1	2.80	0.018	0.055
Methylcyclo pentane	6	12	84	0.395	43.8	38.2	23.0	15.2	2.73	0.019	0.061
Cyclohexane	6	12	84	0.358	43.8	38.2	23.0	15.2	2.75	0.019	0.061

Table B-2-4 continued on the next page

Table B-2-4 continuing from the last page

Fluid	**C**	**H**	**M (g/mole)**	**ΔH_v**	**ΔH_T**	**ΔH_{ch}**	**ΔH_{con}**	**ΔH_{rad}**	**y_{co2}**	**y_{co}**	**y_{sm}**
				kJ/g				**g/g**			
Normal Alkanes	7	14	98	0.365	43.4	37.5	22.3	15.2	2.70	0.021	0.066
Ethylcyclo hexane	8	16	112	0.353	43.2	36.9	21.7	15.2	2.66	0.021	0.069
Dimethylcyclo hexane	8	16	112	0.300	43.2	36.9	21.7	15.2	2.66	0.021	0.069
Cyclooctane	8	16	112		43.2	36.9	21.7	15.2	2.64	0.021	0.069

Table B-2-5. Thermophysical Properties of Unsaturated Aliphatic Hydrocarbons

Fluid	Composition		M (g/mole	Sp gr	T_b (°C)	s (g/g)	C_{st} (%)	T_{flash} (°C)	T_a(°C)	c_P (kJ/kg-K)		LFL (%)	UFL (%)
	C	H								Liquid	Vapor		
Ethylene	2	4	28	0.97	-104	14.7	6.53		490			2.7	36
Propylene	3	6	42	1.45	-47	14.7	4.45		460			2.4	11
Butylene	4	8	56	1.94	-6.3	14.7	3.37		385			1.6	10
Pentene	5	10	70	2.42	3.7	14.7	2.72	-18	275	2.22	1.57	1.4	8.7
Hexene	6	12	84			14.7				2.18	1.57		
Heptene	7	14	98			14.7				2.16	1.58		
Octene	8	16	112			14.7				2.16	1.59		
Nonene	9	18	126			14.7							
Decene	10	20	140			14.7				2.15	1.60		
Dodecene	12	24	168			14.7				2.15	1.60		
Tridecene	13	26	182			14.7							
Tetradecene	14	28	196			14.7							
Hexadecene	16	32	224			14.7				2.16	1.61		
Octadecene	18	36	252			14.7							
Polyethylene	2	4	601			14.7							
Polypropylene	3	6	720			14.7							
Cyclohexene	6	10	82	2.8	83	14.2	2.40		310			1.2	
Methylcyclohexene	7	12	96			14.3							
Pinene	10	16	136	4.7	156	14.1	1.47	33	255			0.7	
Acetylene	2	2	26	0.91	-84	13.2	7.73		305			2.5	100
Heptyne	7	12	96			14.3							
Octyne	8	14	110			14.4							
Decyne	10	18	138			14.4							
Dodecyne	12	22	166			14.5							
1,3 Butadiene	4	6	54	1.87	-4.4	14.0	3.67		420	2.29	1.47	2.0	12

Table B-2-6. Combustion Properties of Unsaturated Aliphatic Hydrocarbons

Fluid	C	H	M g/mole	H_v	H_T	H_{ch}	H_{con}	H_{rad}	y_{co2}	y_{co}	y_{sm}
				kJ/g					g/g		
Normal Alkenes											
Ethylene	2	4	28	0.516	48.0	41.5	27.3	14.2	2.75	0.013	0.076
Propylene	3	6	42	0.437	46.4	40.5	25.6	14.9	2.76	0.017	0.070
Butylene	4	8	56	0.398	45.6	40.0	24.8	15.2	2.78	0.019	0.067
Pentene	5	10	70	0.314	45.2	39.7	24.2	15.5	2.76	0.021	0.065
Hexene	6	12	84	0.388	44.9	39.4	23.9	15.5	2.78	0.021	0.064
Heptene	7	14	98	0.369	44.6	39.3	23.7	15.6	2.77	0.022	0.063
Octene	8	16	112		44.5	39.2	23.5	15.7	2.76	0.022	0.062
Nonene	9	18	126		44.3	39.1	23.3	15.8	2.75	0.022	0.062
Decene	10	20	140	0.306	44.2	39.0	23.2	15.8	2.75	0.022	0.061
Dodecene	12	24	168	0.313	44.1	38.9	23.1	15.8	2.74	0.023	0.061
Tridecene	13	26	182	0.299	44.0	38.9	23.0	15.9	2.74	0.023	0.061
Tetradecene	14	28	196		44.0	38.8	22.9	15.9	2.73	0.023	0.060
Hexadecene	16	32	224	0.292	43.9	38.8	22.8	16.0	2.73	0.023	0.060
Octadecene	18	36	252		43.8	38.7	22.8	15.9	2.72	0.023	0.060
Cyclic Alkenes											
Cyclohexene	6	10	82		43.0	35.7	20.2	15.5	2.64	0.029	0.085
Methylcyclohexene	7	12	96		43.1	35.8	19.8	16.0	2.65	0.029	0.085
Normal Alkynes											
Acetylene	2	2	26	0.751	47.8	36.7	18.7	18.0	2.53	0.042	0.096
Heptyne	7	12	96		44.8	36.0	18.8	17.2	2.56	0.036	0.094
Octyne	8	14	110		44.7	35.9	18.9	17.0	2.53	0.036	0.094
Decyne	10	18	138		44.5	35.9	18.9	17.0	2.55	0.035	0.094
Dodecyne	12	22	166		44.3	35.9	18.9	17.0	2.53	0.035	0.094
Diene											
1,3 Butadiene	4	6	54	0.507	44.6	33.6	15.4	18.2	2.41	0.048	0.125

Table B-2-7. Thermophysical Properties of Aromatic Hydrocarbons

Fluid	Composition		M (g/mole)	Sp gr	T_b (°C)	s (g/g)	C_{st} (%)	T_{flash} (°C)	T_a (°C)	c_P (kJ/kg-K)		LFL (%)	UFL (%)
	C	H								Liquid	Vapor		
Benzene	6	6	78	2.69	80	13.2	2.72	-11	560	1.74	1.05	1.3	7.9
Toluene	7	8	92	3.18	111	13.4	2.27	4	480	1.70	1.13	1.2	7.1
Styrene	8	8	104	3.6	145	13.2	2.05	32	490			1.1	6.1
Ethylbenzene	8	10	106	3.67	136	13.6	1.96	15	430	1.76	1.21	1.0	6.7
Xylene	8	10	106	3.67	144	13.6	1.96	32	530	1.72	1.20	1.1	6.4
Indene	9	8	116			13.0							
Propylbenzene	9	12	120			13.7							
Trimethyl benzene	9	12	120			13.7				1.81	1.29		
Cumene	9	12	120	4.15	152	13.7	1.72	44	425			0.88	6.5
Naphthalene	10	8	128	4.4	218	12.9	1.71	79	526			0.88	5.9
Tetralin	10	12	132	4.6	208	13.5	1.58	71	385			0.84	5.0
Butylbenzene	10	14	134	4.6	183	13.8	1.53	71	410			0.82	5.8
Diethylbenzene	10	14	134			13.8							
p-Cymene	10	14	134	4.63	177	13.8	1.53	47	435			0.85	6.5
Methyl naphthalene	11	10	142		245	13.1	1.53		530			0.80	
Pentylbenzene	11	16	148			13.9							
Dimethyl naphthalene	12	12	156			13.2							
Cyclohexyl benzene	12	16	160			13.7							
Diisopropyl benzene	12	18	162			14.0							
Triethylbenzene	12	18	162			14.0							
Triamylbenzene	21	36	288			14.3							

Table B-2-8. Combustion Properties of Aromatic Hydrocarbons

Fluid	C	H	M	H_v	H_T	H_{ch}	H_{con}	H_{rad}	y_{co2}	y_{co}	y_s
			g/mole	kJ/g					g/g		
Benzene	6	6	78	0.432	40.1	27.6	11.2	16.5	4.53	0.067	0.181
Toluene	7	8	92	0.362	39.7	27.7	11.2	16.5	3.88	0.066	0.178
Styrene	8	8	104		39.4	27.8	11.2	16.6	3.41	0.065	0.177
Ethylbenzene	8	10	106		39.4	27.8	11.2	16.6	3.39	0.065	0.177
Xylene	8	10	106	0.347	39.4	27.8	11.2	16.6	3.39	0.065	0.177
Indene	9	8	116		39.2	27.9	11.3	16.6	3.04	0.065	0.176
Propylbenzene	9	12	120		39.2	27.9	11.3	16.6	3.01	0.065	0.175
Trimethyl benzene	9	12	120		39.2	27.9	11.3	16.6	3.01	0.065	0.175
Cumene	9	12	120		39.2	27.9	11.3	16.6	3.01	0.065	0.175
Naphthalene	10	8	128	0.558	39.0	27.9	11.3	16.6	2.74	0.065	0.175
Tetralin	10	12	132		39.0	27.9	11.4	16.5	2.71	0.064	0.174
Butylbenzene	10	14	134		39.0	27.9	11.4	16.5	2.70	0.064	0.174
Diethylbenzene	10	14	134		39.0	27.9	11.4	16.5	2.70	0.064	0.174
p-Cymene	10	14	134		39.0	27.9	11.4	16.5	2.70	0.064	0.174
Methyl naphthalene	11	10	142		38.9	28.0	11.4	16.6	2.49	0.064	0.174
Pentylbenzene	11	16	148		38.8	28.0	11.4	16.6	2.45	0.064	0.173
Dimethyl naphthalene	12	12	156		38.8	28.0	11.4	16.6	2.27	0.064	0.173
Cyclohexyl benzene	12	16	160		38.7	28.0	11.4	15.5	2.25	0.064	0.173
Diisopropyl benzene	12	18	162		38.7	28.0	11.4	16.6	2.24	0.064	0.173
Triethylbenzene	12	18	162		38.7	28.0	11.4	16.6	2.24	0.064	0.173
Triamylbenzene	21	36	288		38.1	28.2	11.6	16.6	1.23	0.063	0.169

Table B-2-9. Thermophysical Properties of Oxygenated Fluids

Fluid	**Composition**			**M (g/mole)**	**Sp gr**	**T_b (^oC)**	**s (g/g)**	**C_{st} (%)**	**T_{flash} (^oC)**	**T_a (^oC)**	**c_P (kJ/kg-K)**		**LFL (%)**	**UFL (%)**
	C	**H**	**O**								**Liquid**	**Vapor**		
Aliphatic Alcohols														
Methyl alcohol	1	4	1	32	1.11	65	6.4	12.25	11	385	2.55	1.37	6.7	36.0
Ethyl alcohol	2	6	1	46	1.59	79	9.0	6.53	13	365	2.46	1.43	3.3	19.0
n-Propyl alcohol	3	8	1	60	2.07	97	10.3	4.45	25	440	2.39	1.46	2.2	14.0
Isopropyl alcohol	3	8	1	60	2.10	82	10.3	4.45	12	399			2.2	12.0
n-Butyl alcohol	4	10	1	74	2.56	117	11.1	3.37	29	365			1.7	12.0
Isobutyl alcohol	4	10	1	74	2.60	108	11.1	3.37	28	427			1.7	11.0
sec-Butyl alcohol	4	10	1	74	2.60	100	11.1	3.37	24	405			1.7	9.8
ter-Butyl alcohol	4	10	1	74	2.60	82	11.1	3.37	11	480			1.9	9.0
n-Amyl alcohol	5	12	1	88	3.04	137	11.7	2.72	38	300			1.4	10.0
Isobutyl carbinol	5	12	1	88			11.7							
sec Butyl carbinol	5	12	1	88			11.7							
Methylpropyl carbinol	5	12	1	88			11.7							
Dimethylethyl carbinol	5	12	1	88			11.7							
n-Hexyl alcohol	6	14	1	102	3.53	158	12.1	2.27	63	300			1.2	
Dimethylbutyl alcohol	6	14	1	102			12.1							
Ethylbutyl alcohol	6	14	1	102			12.1							
Allyl alcohol	3	6	1	58	2.00	97	9.5	4.97	21	378			2.5	18.0
Cyclohexanol	6	12	1	100	3.50	161	11.7	2.40	68	300			1.2	

Table B-2-9 continuing on the next page

Table B-2-9 continued from the previous page

Fluid	Composition			M (g/mole)	Sp gr	T_b (^{o}C)	s (g/g)	C_{st} (%)	T_{flash} (^{o}C)	T_a (^{o}C)	c_p (kJ/kg-K)		LFL (%)	UFL (%)
	C	H	O								Liquid	Vapor		
Aliphatic Ketones														
Acetone	3	6	1	58	2.01	56	9.5	4.97	-18	465	2.18	1.30	2.6	13.0
Methylethyl ketone	4	8	1	72	2.49	80	10.5	3.67	-6	516			1.9	11.0
Cyclohexanone	6	10	1	98	3.40	156	11.2	2.55	44	420			1.1	
Di-Acetone alcohol	6	12	2	116			9.5							
Aliphatic Esters														
Ethyl formate	3	6	2	74	2.56	55	6.5	5.65	-20	456			2.8	16.0
n-Propyl formate	4	8	2	88			7.8							
n-Butyl formate	5	10	2	102	3.53	107	8.8	3.12	18	322			1.7	8.2
Methyl acetate	3	6	2	74	2.56	57	6.5	5.65	-10	502			3.2	16.0
Ethyl acetate	4	8	2	88	3.04	77	7.8	4.02	-4	427			2.2	11.0
n-Propyl acetate	5	10	2	102	3.53	102	8.8	3.12	14	450			1.8	8.0
n-Butyl acetate	6	12	2	116	4.01	127	9.5	2.55	22	425			1.4	8.0
Isobutyl acetate	6	12	2	116	4	118	9.5	2.55	18	421			2.4	10.5
Amyl acetate	7	14	2	130	4.5	149	10.0	2.16	25	360			1.0	7.1
Cyclohexyl acetate	8	14	2	142			10.2							
Octyl acetate	10	20	1	172			11.2							
Ethyl acetoacetate	6	10	3	130			7.4							
Methyl propionate	4	8	2	88	3.04	80	7.8	4.02	-2	469			2.4	13
Ethyl propionate	5	10	2	102	3.53	99	8.8	3.12	12	440			1.8	11
n-Butyl propionate	7	14	2	130			10.0							
Isobutyl propionate	7	14	2	130			10.0							
Amyl propionate	8	16	2	144		169	10.5	1.87	41	380			1.0	
Methyl butyrate	5	10	2	102	3.52	102	8.8	3.12	14					

Table B-2-9 continuing on the next page

Table B-2-9 continued from the previous page

Fluid	Composition			M (g/mole)	Sp gr	T_b (°C)	s (g/g)	C_{st} (%)	T_{flash} (°C)	T_a (°C)	c_P (kJ/kg-K)		LFL (%)	UFL (%)
	C	H	O								Liquid	Vapor		
Aliphatic Esters continuing														
Ethyl butyrate	6	12	2	116	4	121	9.5	2.55	26	463				
Propyl butyrate	7	14	2	130			10.0							
n-Butyl butyrate	8	16	2	144			10.5							
Isobutyl butyrate	8	16	2	144			10.5							
Ethyl laurate	14	28	1	228			12.0							
Ethyl oxalate	4	6	4	102			6.1							
Ethyl malonate	5	8	4	132			7.7							
Ethyl lactate	5	10	3	118	4.1	155	7.0	3.37	46	400			1.5	
Butyl lactate	7	14	3	146			8.5							
Amyl lactate	8	16	3	160			9.0							
Ethyl carbonate	5	10	3	118			7.0							
Other Aliphatic Fluids														
Monoethyl ether	4	10	2	90			8.4							
Monoethyl ether acetate	6	12	3	132			7.8							
Monoethyl ether diacetate	6	10	4	146			6.1							
Glycerol triacetate	9	14	6	218			6.0							
Aromatic Fluids														
Benzaldehyde	7	6	1	106			10.4							
Benzyl alcohol	7	8	1	108	3.72	205	10.8	2.4	101	436	2.02			
Cresylic acid	8	8	1	136			9.1							
Ethyl benzoate	9	10	2	150			9.6							
Phenylbutyl ketone	11	14	1	162			11.9							

Table B-2-10. Combustion Properties of Oxygenated Fuels

Fluid	C	H	O	M (g/mole)	ΔH_v	ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}	y_{co2}	y_{co}	y_{sm}
					kJ/g					g/g		
Aliphatic Alcohols												
Methyl alcohol	1	4	1	32	1.101	20.0	19.1	16.1	3.0	1.32	0.001	0.001
Ethyl alcohol	2	6	1	46	0.837	27.7	25.6	19.0	6.5	1.76	0.001	0.008
n-Propyl alcohol	3	8	1	60	0.686	31.8	29.0	20.6	8.5	2.00	0.003	0.015
Isopropyl alcohol	3	8	1	60	0.667	31.8	29.0	20.6	8.5	2.00	0.003	0.015
n-Butyl alcohol	4	10	1	74	0.621	34.4	31.2	21.6	9.6	2.15	0.004	0.019
Isobutyl alcohol	4	10	1	74	0.578	34.4	31.2	21.6	9.6	2.15	0.004	0.019
sec-Butyl alcohol	4	10	1	74	0.575	34.4	31.2	21.6	9.6	2.15	0.004	0.019
ter-Butyl alcohol	4	10	1	74	0.575	34.4	31.2	21.6	9.6	2.15	0.004	0.019
n-Amyl alcohol	5	12	1	88	0.501	36.2	32.7	22.2	10.4	2.25	0.005	0.022
Isobutyl carbinol	5	12	1	88		36.2	32.7	22.2	10.4	2.25	0.005	0.022
sec Butyl carbinol	5	12	1	88		36.2	32.7	22.2	10.4	2.25	0.005	0.022
Methylpropyl carbinol	5	12	1	88		36.2	32.7	22.2	10.4	2.25	0.005	0.022
Dimethylethyl carbinol	5	12	1	88	0.458	36.2	32.7	22.2	10.4	2.25	0.005	0.022
n-Hexyl alcohol	6	14	1	102	0.458	37.4	33.7	22.7	11.0	2.32	0.006	0.024
Dimethylbutyl alcohol	6	14	1	102		37.4	33.7	22.7	11.0	2.32	0.006	0.024
Ethylbutyl alcohol	6	14	1	102		37.4	33.7	22.7	11.0	2.32	0.006	0.024
Allyl alcohol	3	6	1	58	0.763	31.4	28.6	20.4	8.2	2.07	0.003	0.014
Cyclohexanol	6	12	1	100	0.460	37.3	33.6	22.6	11.0	2.38	0.005	0.024
Aliphatic Ketones												
Acetone	3	6	1	58	0.521	29.7	27.9	20.3	7.6	2.13	0.003	0.014
Methylethyl ketone	4	8	1	72	0.474	32.7	30.6	22.1	8.6	2.28	0.004	0.018
Cyclohexanone	6	10	1	98	0.429	35.9	33.7	24.1	9.6	2.53	0.005	0.023
Di-Acetone alcohol	6	12	2	116		37.3	35.0	24.9	10.1	2.63	0.006	0.026

Table B-2-10 continuing on the next page

Table B-2-10 continued from the previous page

Fluid	C	H	O	M (g/mole)	ΔH_v	ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}	y_{co2}	y_{co}	y_{sm}
					kJ/g					g/g		
Esters and Other Types of Fluids												
Ethyl formate	3	6	2	74	0.425	20.2	19.9	13.5	6.3	1.76	0.003	0.011
n-Propyl formate	4	8	2	88	0.390	23.9	23.4	15.4	8.0	1.95	0.005	0.019
n-Butyl formate	5	10	2	102	0.381	26.6	26.0	16.7	9.3	2.11	0.007	0.025
Methyl acetate	3	6	2	74	0.437	20.2	19.9	13.5	6.3	1.76	0.003	0.011
Ethyl acetate	4	8	2	88	0.395	23.9	23.4	15.4	8.0	1.95	0.005	0.019
n-Propyl acetate	5	10	2	102	0.366	26.6	26.0	16.7	9.3	2.11	0.007	0.025
n-Butyl acetate	6	12	2	116		28.7	28.0	17.8	10.2	2.22	0.008	0.029
Isobutyl acetate	6	12	2	116	0.335	28.7	28.0	17.8	10.2	2.22	0.008	0.029
Amyl acetate	7	14	2	130	0.338	30.3	29.5	18.6	11.0	2.30	0.009	0.033
Cyclohexyl acetate	8	14	2	142		31.5	30.6	19.1	11.5	2.40	0.010	0.035
Octyl acetate	10	20	1	172		33.6	32.6	20.2	12.5	2.48	0.012	0.039
Ethyl acetoacetate	6	10	3	130	0.381	30.3	29.5	18.6	11.0	2.24	0.009	0.033
Methyl propionate	4	8	2	88	0.397	23.9	23.4	15.4	8.0	1.95	0.005	0.019
Ethyl propionate	5	10	2	102	0.364	26.6	26.0	16.7	9.3	2.11	0.007	0.025
n-Butyl propionate	7	14	2	130		30.3	29.5	18.6	11.0	2.30	0.009	0.033
Isobutyl propionate	7	14	2	130		30.3	29.5	18.6	11.0	2.30	0.009	0.033
Amyl propionate	8	16	2	144	0.307	31.6	30.8	19.2	11.6	2.38	0.010	0.035
Methyl butyrate	5	10	2	102	0.365	26.6	26.0	16.7	9.3	2.11	0.007	0.025
Ethyl butyrate	6	12	2	116	0.342	28.7	28.0	17.8	10.2	2.22	0.008	0.029
Propyl butyrate	7	14	2	130	0.331	30.3	29.5	18.6	11.0	2.30	0.009	0.033
n-Butyl butyrate	8	16	2	144		31.6	30.8	19.2	11.6	2.38	0.010	0.035
Isobutyl butyrate	8	16	2	144	0.299	31.6	30.8	19.2	11.6	2.38	0.010	0.035
Ethyl laurate	14	28	1	228		37.2	35.6	26.5	9.1	2.57	0.008	0.031
Ethyl oxalate	4	6	4	102		28.7	27.7	21.3	6.4	2.01	0.001	0.003

Table B-2-10 continuing on the next page

Table B-2-10 continued from the previous page

Fluid	C	H	O	M (g/mole)	ΔH_v	ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}	y_{co2}	y_{co}	y_{sm}
					kJ/g					g/g		
Esters and Other Types of Fluids Continuing												
Ethyl malonate	5	8	4	132		32.2	31.0	23.4	7.5	2.24	0.003	0.015
Ethyl lactate	5	10	3	118		30.8	29.6	22.5	7.1	2.14	0.001	0.010
Butyl lactate	7	14	3	146		33.3	32.0	24.1	7.9	2.32	0.004	0.018
Amyl lactate	8	16	3	160		34.3	32.9	24.7	8.2	2.38	0.005	0.021
Ethyl carbonate	5	10	3	118		30.8	29.6	22.5	7.1	2.14	0.001	0.010
Monoethyl ether	4	10	2	90		26.7	25.8	20.0	5.8	1.87	0.001	0.007
Monoethyl ether acetate	6	12	3	132		32.2	31.0	23.2	7.7	2.25	0.001	0.011
Monoethyl ether diacetate	6	10	4	146		33.3	32.0	24.2	7.9	2.32	0.001	0.009
Glycerol triacetate	9	14	6	218		36.9	35.4	26.3	9.1	2.56	0.002	0.011
Aromatic Fluids												
Benzaldehyde	7	6	1	106	0.460	32.4	21.2	8.1	13.2	1.85	0.062	0.166
Benzyl alcohol	7	8	1	108	0.546	32.6	22.9	9.8	13.1	1.97	0.050	0.137
Cresylic acid	8	8	1	136		34.0	25.1	11.6	13.5	1.88	0.039	0.107
Ethyl benzoate	9	10	2	150	0.334	34.5	27.4	14.1	13.3	2.07	0.030	0.084
Phenylbutyl ketone	11	14	1	162		34.8	26.3	12.6	13.7	1.96	0.041	0.115

Table B-2-11. Thermophysical Properties of Nitrogen Containing Fluids

Fluid	Composition			M	Sp gr	T_b (°C)	s (g/g)	C_{st}	T_{flash}	T_a (°C)	LFL	UFL
	C	H	N	(g/mole)	(air=1)			(%)	(°C)		(%)	(%)
Aliphatic												
Diethylamine	4	11	1	73	2.5	56	14.6	3.01		312	1.8	10
n-Butylamine	4	11	1	73	2.5	78	14.6	3.01	-12	312	1.8	
Sec-butylamine	4	11	1	73			14.6					
Triethylamine	6	15	1	101	3.5	89	14.6	2.10	7		1.2	8
Di-n-butylamine	8	19	1	129			14.6					
Tri-n-butylamine	12	27	1	185			14.7					
Aromatic												
Pyridine	5	5	1	79	2.7	116	12.6	3.24	20	482	1.8	12
Aniline	6	7	1	93	3.2	184	12.9	2.63	70	615	1.2	8.3
Picoline	6	7	1	93			12.9					
Toluidine	7	9	1	107			13.2					
Dimethylaniline	8	11	1	121			13.3					
Quinoline	9	7	1	129	4.5	238	12.5	1.91		480	1.0	
Quinaldine	10	9	1	143			12.7					
Butylaniline	10	15	1	149			13.6					

Table B-2-12. Combustion Properties of Nitrogen Containing Fluids

Fluid	C	H	N	M g/mole	ΔH_v	ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}	y_{co2}	y_{co}	y_{sm}
					kJ/g					g/g		
Aliphatic												
Diethylamine	4	11	1	73	0.419	38.0	34.0	21.3	12.6	2.14	0.012	0.039
n-Butylamine	4	11	1	73	0.429	38.0	34.0	21.3	12.6	2.14	0.012	0.039
Sec-butylamine	4	11	1	73		38.0	34.0	21.3	12.6	2.14	0.012	0.039
Triethylamine	6	15	1	101		39.6	35.3	22.0	13.3	2.31	0.014	0.044
Di-n-butylamine	8	19	1	129		40.6	36.1	22.4	13.7	2.41	0.014	0.047
Tri-n-butylamine	12	27	1	185	0.280	41.6	37.0	22.9	14.1	2.52	0.015	0.049
Aromatic												
Pyridine	5	5	1	79	0.511	32.2	24.0	11.5	12.5	2.04	0.037	0.104
Aniline	6	7	1	93	0.509	33.8	25.0	11.7	13.3	2.07	0.043	0.119
Picoline	6	7	1	93	0.447	33.8	25.0	11.7	13.3	2.07	0.043	0.119
Toluidine	7	9	1	107	0.495	34.9	25.8	11.9	13.9	2.10	0.048	0.130
Dimethylaniline	8	11	1	121	0.391	35.7	26.4	12.1	14.3	2.11	0.051	0.139
Quinoline	9	7	1	129	0.408	36.1	26.7	12.1	14.5	2.23	0.052	0.143
Quinaldine	10	9	1	143		36.7	27.1	12.2	14.8	2.24	0.055	0.149
Butylaniline	10	15	1	149		37.0	27.2	12.2	15.0	2.13	0.056	0.151

Table B-2-13. Combustion Properties of Sulfur Containing Fluids

Fluids	C	H	S	M g/mole	ΔH_v	ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}	y_{co2}	y_{co}	y_s
						kJ/g				g/g		
Heptyl Mercaptan	7	16	1	132		33.7	30.4	18.1	12.3	2.10	0.013	0.044
Decyl Mercaptan	10	22	1	174	0.284	34.9	31.1	18.4	12.7	2.24	0.016	0.051
Dodecyl Mercaptan	12	26	1	202		35.5	31.4	18.6	12.8	2.29	0.017	0.054
Hexyl Sulfide	12	26	1	202		35.5	31.4	18.6	12.8	2.29	0.017	0.054
Heptyl Sulfide	14	30	1	230		35.9	31.6	18.7	13.0	2.34	0.018	0.057
Octyl Sulfide	16	34	1	258		36.3	31.8	18.8	13.1	2.38	0.019	0.059
Decyl Sulfide	20	42	1	314		36.8	32.1	18.9	13.2	2.43	0.020	0.061
Thiophene	4	4	1	84	0.436	31.9	23.4	10.8	12.6	1.51	0.031	0.086
Methylthiophene	5	6	1	98	0.379	33.2	24.1	10.9	13.2	1.59	0.039	0.107
Thiophenol	6	6	1	110	0.431	34.1	24.6	11.0	13.6	1.69	0.045	0.122
Thiocresol	7	8	1	124		34.9	25.0	11.0	14.0	1.73	0.050	0.135
Cresolmethylsulfide	8	11	1	155		36.2	25.7	11.1	14.5	1.56	0.058	0.155

APPENDIX B-3

ENGINE COMPARTMENT FLUIDS EXAMINED AND THEIR THERMOPHYSICAL AND FIRE PROPERTIES

(References in Chapter II)

I. INTRODUCTION

The engine compartment fluids are used for the lubrication of the engine (to separate moving surfaces to minimize friction and wear), power steering, automatic transmission, braking, prevention of freezing of water and engine and for washing the windshield [21,22]. Petroleum products are the most dominant lubricants ranging in low viscosity with molecular weights as low as 250 to very viscous lubricants with average molecular weights up to about 1000[1]. The hydrocarbon fluids are complex mixtures of aliphatic hydrocarbons (n-paraffin, iso-paraffin, and cyclic-paraffin), aromatic hydrocarbons, and their mixtures. The physical properties and performance characteristics of the engine compartment fluids depend on the relative distributions of paraffin, aromatic, and alicyclic (naphthenic) components.

For a given molecular size, paraffins, as compared to the other hydrocarbon components, have relatively low viscosity, low density, and higher freezing temperatures. Aromatics have a higher density, darker color, and higher viscosity that change rapidly with temperature. Although aromatics have a higher degree of oxidation stability, they oxidize to form insoluble black sludge at high temperature. Alicyclic oils are characterized by low pour point, low oxidation stability, and other properties intermediate to those of the paraffins and aromatics. Most premium lubricants are paraffinic oils composed of both paraffinic and alicyclic structures with only a minor portion of aromatics. Since the hydrocarbon-based engine compartment fluids are complex mixtures of the hydrocarbons, interpretations of their measured property data are difficult.

In the internal combustion engine, oils are exposed to high thermal and mechanical loads. The most common engine oils are mineral oils with additives. The quality of engine oils depends on the origin and refining of the base oils, the viscosity grade, and the effectiveness of the additives. There are four different additive types: viscosity index improvers (VI), oxidation and corrosion inhibitors, detergents and dispersants, and high-pressure additives (EP).

Mineral oils consist of numerous and varied hydrocarbons and referred to as mixed-base oils, paraffin-base oils (saturated aliphatic hydrocarbons), aromatic-base oils (unsaturated cyclic hydrocarbons such as benzene) or naphthalene-base oils (saturated cyclic hydrocarbons with five or six carbon atoms in the ring, less often with seven or eight atoms).

---

[1] The SAE (Society of Automotive Engineers) viscosity grades 5W, 10W, 15W, 20W, 20, 30, 40, 50, and others are used for classifying oils by viscosity [21, 22]. There are two basic types of oils: single-grade and multi-grade. Multi-grade oils (flat viscosity-temperature curve) are the most common type in use [21,22].

Type of transmission and the load to which the oil is subjected determines the quality of the transmission oil. Oils containing additives are used in motor vehicle transmissions. The base oil has to be high-quality oil. The SAE viscosity designations for transmission oils are 75, 80, 90, 140, and 250.

Additives are used in almost all the lubricants. Zinc dialkyl dithiophosphates are the primary oxidation inhibitors (0.5 to 1.0 %). Alkyl and aryl disulfides and polysulfides, dithiocarbamates, and sulfurized fats are common additives for anti-wear and extreme pressure agents. Fatty acids with 12 to 18 carbon atoms and fatty alcohols or esters of fatty acids such as the glycerides of rapeseed and lard oil are commonly used as friction modifiers. Detergents and dispersants are used at 2 to 20%. The detergents are calcium, sodium, and magnesium salts of alkylbenzenesulfonic acids, alkylphenols, sulfur-and methylene-coupled alkyl phenols, carboxylic acids, and alkylphosphonic acids. Polybutenylsuccinic acid derivatives are commonly used as dispersants. Polymethacrylate polymers (1 % or less) are used as pour-point depressants and to increase viscosity. The common polymers used to increase viscosity are polyisobutylenes, polymethacrylates, and polyalkylstyrenes.

Although petroleum based oils are low cost oils, production of synthetic oils has been expanding to take advantage of the special properties such as stability at extreme temperatures, chemical inertness, fire resistance, low toxicity, and environmental compatibility.

The engine compartment fluids used as brake fluids are polyglycol ethers; antifreeze is ethylene or propylene glycol, engine coolants are 50:50 mixtures of antifreeze and water and the windshield washing fluids are mixtures of methanol and water.

II. ENGINE COMPARTMENT FLUIDS SELECTED FOR EXAMINATION

The new and used engine compartment fluids selected for the examination are listed in Table B-3-1 and Table B-3-2 respectively. The majority of the fluids were hydrocarbon-based fluids (16 new and 25 used). The other fluids examined were based on glycols (five new and one used) and alcohols (two new and two used).

Table B-3-1. New Engine Compartment Fluids Selected for Examination [8-11]

Sample	Brand	Type	Lot
Motor Oils (Petroleum):Hydrocarbon Mixtures			
B10FF001	Havoline	SAE 5W30	113000549910
B10FF002	Quaker State	SAE 5W30	3C100898-1338
B10FF003	Castrol GTX	SAE 5W30	V82822153F9
B10FF004	Valvoline	SAE 5W30	B229FA129086
B10FF005	Mobil	SAE 10W30	
B10FF006	Pennzoil	SAE 5W30	SC051STK3609L2 12:52:06
Synthetic Motor Oils (Synthetic): Hydrocarbon Mixtures			
B10FF007	Mobil 1	SAE 5W30	X08B9A2
B10FF008	Royal Purple	SAE 10W30	8050144
B10FF009	Castrol Syntec	SAE 5W30	V904310759A9
Gear Lubrication Fluid: Hydrocarbon Mixture			
B10FF010	Quaker State	SAE 80W90	03,03,99
Power Steering Fluids: Hydrocarbon Mixtures			
B10FF014	Valvoline	SynPower	D298X
B10FF015	Pyroil		B229C1
B10FF016	Prestone		AS261P P-1219
Automatic Transmission Fluids: Hydrocarbon Mixtures			
B10FF017	Quaker State	DexronIII/Mercon	3C022499-1399
B10FF018	Sunoco	DexronIII/Mercon	M940209G340141M902206:04
Brake Fluids (Polyglycol Ethers): Non-Hydrocarbon Mixtures			
B10FF011	Prestone	Dot 3	
B10FF012	Albany	Dot 3	
B10FF013	Coastal	Dot 3	
Antifreeze (Ethylene or Propylene Glycol): Non-Hydrocarbon Mixtures			
B10FF021	Prestone	Ethylene glycol	2HA9036
B10FF022	Sierra	Propylene glycol	9068
Engine Coolants (Glycol-Water 1:1): Non-Hydrocarbon Mixtures			
B10FF035	Prestone	Ethylene glycol	50%B10FF021 + 50 % water
B10FF036	Sierra	Propylene glycol	50% B10FF022 + 50 % water
Windshield Washing Fluids (Methanol-Water): Non-Hydrocarbon Mixtures			
B10FF019	JetGo	Summer	
B10FF020	Peak	Winter	

Table B-3-2. Used Engine Compartment Fluids Selected for Examination [8-11]

Sample	Fluid Information			Vehicle Information				Miscellaneous Information
	Brand	Grade	Mileage	Mileage	Make	Model	Year	
Motor Oils (Petroleum):Hydrocarbon Mixtures								
B10FF023	Mobil	SAE 5W30	1,007	26,812	Pontiac	Firebird	1997	Short trip with burn off
B10FF024	Mobil	SAE 5W30	230	Unknown	Chevrolet	Express Van	1997	Cold start, 112 Short trips, 230 miles accumulated
B10FF025	Texaco	SAE 10w30	1,763	11,801	Unknown	Unknown	Unknown	Unknown
B10FF026	Pennzoil	SAE 15w40	575	12,607	Chevrolet	3500 Van	1992	High load highway
B10FF027	Mobil	SAE 5w30	542	19,580	Chevrolet	Suburban	1997	City driving, 542 miles, short trips
B10FF028	Mobil	SAE 10w30	3,000	60,410	Buick	Skylark	1995	50 % city, 50% highway
B10FF029	Pennzoil	SAE 5w30	4,475	63,775	Chevrolet	Lumina	1994	75 % highway, 25 % city
B10FF030	Motor Craft	SAE 5W30	3,000	156,238	Ford	Explorer	1992	75 % highway, 25 % city
B10FF031	Mobil	SAE 5W30	7,500	34,927	Chevrolet	Venture	1998	75 % highway, 25 % city
B10FF037	Sunfill SJ	SAE 5W30	7,282	18,384	GMC	Suburban	1999	50 % highway, 50 % city
B10FF038	Sunfill SJ	SAE 5W30	2,713	2,713	Chevrolet	M-Van	Unknown	Short trips, many start/stops
B10FF039	Sunfill SJ	SAE 5W30	Unknown	8,423	Chevrolet	S-10 pick-up	1991	Unknown
B10FF041	Sunfill SJ	SAE 5W30	2,150	2,150	Chevrolet	Van Express	1996	Cold starts, low speed, short trips
B10FF042	Sunfill SJ	SAE 10W30	463	4,633	Buick	LeSabre	1996	Short trips, start/stops
B10FF043	Sunfill SJ	SAE 5W30	Unknown	12,766	GMC	S-10 pick up	1994	Unknown
B10FF044	Sunfill SJ	SAE 10W30	127	1,558	Pontiac	Firebird	1998	Hard driving, seed, and RPM
B10FF045	Sunfill SJ	SAE 10W30	7,304	20,304	Pontiac	Grand Prix	1998	Unknown
B10FF046	Sunfill SJ	SAE 10W30	8,462	17,704	Pontiac	Grand Prix	1998	Hard driving

Table B-3-2 continuing on the next page

Table B-3-2 continued from the previous page

Sample	Fluid Information			Vehicle Information				Miscellaneous Information
	Brand	Grade	Mileage	Mileage	Make	Model	Year	
Motor Oils (Synthetic): Hydrocarbon Mixtures								
B10FF032	Royal purple	SAE 10w30	2,500	205,770	Dodge	Dakota	1991	Unknown
B10FF033	Mobil 1	SAE 5W30	7,500	48,092	Chevrolet	Astro Van	1995	Unknown
B10FF040	Mobil 1	SAE 5W30	1,257	23,840	Oldsmobile	Bravada	1994	Short trips, start/stops
B10FF047	Mobil 1	SAE 5W30	81	9523	Chevrolet	Corvette	1993	Hard driving, speed, RPM
B10FF048	Mobil 1	SAE 5W30	60	6022	Chevrolet	Corvette	1995	Hard driving, speed, RPM
Power Steering Fluid: Hydrocarbon Mixture								
B10FF051	Unknown	Unknown						Pooled from many vehicles
B10FF053	Good Wrench	Cold Climate						
Automatic Transmission Fluid: Hydrocarbon Mixture								
B10FF034	Quaker State	DextronIII/ Mercon	30,000	60,614	Buick	Skylark	1995	50 % highway, 50 % city
Brake Fluid (Polyglycol Ether): Non-Hydrocarbon Mixture								
B10FF052	Unknown	Unknown						Pooled from many vehicles
Engine Coolant (Glycol-Water 1:1): Non-Hydrocarbon Mixtures								
B10FF049	Unknown	Unknown	Unknown	23,840	Oldsmobile	Bravada	1991	Short trips, start/stops
B10FF050	Dexcool	Unknown	Unknown	8,423	Chevrolet	S-10 pick-up	1991	Unknown

III. QUANTIFIED THERMOPHYSICAL AND FIRE PROPERTIES OF ENGINE COMPARTMENT FLUIDS

The quantified thermophysical and fire properties of the engine compartment fluids are listed in Tables B-3-3 to B-3-14.

3.1 Density of Engine Compartment Fluids

The engine compartment fluid densities were determined from the API gravity measured by the ASTM D287-92 Standard Test Method (Appendix B-1), using the following relationship given in the Standard with density of water at 60 ^{o}F (15.6 ^{o}C) [11]

API specific gravity, deg = (141.5/specific gravity 60/60 ^{o}F)-131.5 (B-3-1)

In addition, fluid densities were also determined from the measured mass and volume of the fluids at 20 ^{o}C and densities converted to 16 ^{o}C. The densities of the engine compartment fluids measured by these two methods are listed in Table B-3-3. There is a good agreement between the densities of the fluids determined from these two methods.

Table B-3-3. Densities of Selected Engine Compartment Fluids [11]

Sample	New/ Used	Measured AIP Gravity (deg)	Calculated Density (g/ml)	
			AIP	Mass/Volume
Motor Oils				
B10FF001	**New, Petroleum**	31.8	0.867	0.862
B10FF002		30.6	0.873	0.880
B10FF003		30.6	0.873	0.876
B10FF004		30.3	0.875	0.871
B10FF005		27.7	0.889	0.877
B10FF006		32.1	0.865	0.863
B10FF007	**New, Synthetic**	32.4	0.863	0.864
B10FF008		29.8	0.877	0.882
B10FF009		35.3	0.848	0.842
B10FF023	**Used, Petroleum**	28.0	0.887	0.888
B10FF024		29.8	0.877	0.878
B10FF027		26.5	0.896	0.889
B10FF028		29.9	0.877	0.873
B10FF029		30.0	0.876	0.880
B10FF030		30.2	0.875	0.879
B10FF031		26.7	0.894	0.904

Table B-3-3 continuing on the next page

Table B-3-3 continued from the previous page

Sample	New/ Used	Measured AIP Gravity (deg)	Calculated Density (g/ml)	
			AIP	Mass/Volume
B10FF032	**Used, Synthetic**	28.3	0.885	0.883
B10FF033		21.5	0.925	0.889
Gear Lubrication Fluid				
B10FF010	**New**	25.4	0.902	0.893
Power Steering Fluids				
B10FF014	**New**	33.0	0.860	0.866
B10FF015		31.9	0.866	0.879
B10FF016		30.7	0.872	0.869
B10FF051	**Used**	29.4	0.879	0.879
B10FF053		32.4	0.863	
Automatic Transmission Fluids				
B10FF017	**New**	31.2	0.870	0.876
B10FF018		31.2	0.870	0.876
B10FF034	**Used**	31.2	0.870	0.866
Brake Fluids				
B10FF011	**New**	6.8	1.023	1.033
B10FF012		3.8	1.046	1.042
B10FF013		3.2	1.050	1.052
B10FF052	**Used**	4.3	1.042	1.045
Antifreeze				
B10FF021	**New**	1.1	1.067	1.031
B10FF022		4.2	1.043	1.049
Engine Coolants				
B10FF035	**New**	3.0	1.074	
B10FF036		3.7	1.047	
B10FF050	**Used**	0.4	1.073	1.089
Windshield Washing Fluids				
B10FF019	**New**	17.0	0.953	0.960
B10FF020		18.9	0.941	0.949

3.2 Boiling Point and Distillation Data for the Engine Compartment Fluids

The distillation temperature ranges and boiling points (**T_b**) for selected engine compartment fluids were measured using the ASTM D1120, ASTM D86, and ASTM D2887 Standard Test Methods (Appendix B-1) [11]. In the D1120 test method, **T_b** is defined as the temperature at which a fluid boils at equilibrium, i.e. condensation and distillation of a fluid are in balance. The ASTM D1120 Test Method has been designed for the determination of $\mathbf{T_b}$ values for the engine coolants (glycol-water mixtures). The $\mathbf{T_b}$ values using this Test Method were measured by UEC [11].

In the ASTM D86 Test Method, designed for the distillation of petroleum products, fluid volume distilled at various temperatures is measured. The Test Method is similar to the ASTM D1120 Test Method, except that the condensate is separated from the boiling fluid via a condenser. Values of the initial boiling point ($\mathbf{T_{ib}}$), final boiling point ($\mathbf{T_{fb}}$) and distillation temperature ranges for fluids are measured. The $\mathbf{T_{ib}}$ and $\mathbf{T_{fb}}$, values and distillation temperature ranges using this Test Method were measured by UEC [11].

In the ASTM D2887 Test Method, Gas Chromatograph (GC) is used to separate the fluid components from each other by a heated column. The components elute from the column according to their boiling points, similar to the distillation of a fluid as it is heated. The concentration and molecular weight of the components in the fluids are determined from the standard calibration of the GC column for the retention time versus the boiling points and molecular weights of standard mixtures of fluids with known generic natures of the components and their concentrations. Data using this method were measured by UEC and GM [8,11].

The distillation temperature ranges measured by GM and UEC using the ASTM D86 and ASTM D2887 Test Methods for the selected engine compartment fluids [8,11] are listed in Tables B-3-4 and B-3-7. Very limited data were measured for the $\mathbf{T_b}$ values by the ASTM D1120 Test Method, as the $\mathbf{T_b}$ values for most of the engine compartment fluids were greater than 300 ^{o}C, which is beyond the range of the apparatus at UEC.

3.3 Vaporization

Vaporization behaviors of the selected engine compartment fluids were examined by the Modulated Differential Scanning Calorimetry (MDSC) [10]. The fluids were heated in a hermetically sealed aluminum pans with a pinhole covered by a steel ball to avoid boil over of fluids before the boiling point. Toluene was used as a calibration fluid.

Based on the profile of the endothermic vaporization process, the vaporization temperature range, peak vaporization temperature ($\mathbf{T_{v,peak}}$) and the vaporization energy ($\mathbf{E_v}$) were determined for the selected engine compartment fluids [10]. These data are listed in Table B-3-8 for the selected engine compartment fluids.

From the data listed in Table B-3-8, heat of vaporization (**ΔH_v**) values of the fluids were calculated using Eq. B-2-17 (Appendix B-2) with **T_o** = 25 °C and **T_b** = initial vaporization temperature. The calculated **ΔH_v** values are listed in Table B-3-16. The average values of **ΔH_v** for similar group of engine compartment fluids are listed in Table 2-6 in Chapter II.

3.4 Ignition

Ignition behavior of a fluid is expressed in terms of its flash point (**T_{flash}**), its fire point (**T_{fire}**), its autoignition temperature (**T_a**) and its hot surface ignition temperature (**T_{hot}**). The **T_{flash}** values for the fluids were measured by FM Global using the ASTM D93-97 Standard Test Method, briefly described in Appendix B-1. The **T_a** values for the fluids were measured by UEC using the ASTM E659 Standard Test Method, also briefly described in Appendix B-1. For the measurement of **T_{hot}**, a special test method was developed, which is described in Appendix B-1.

Data for **T_{flash}**, **T_a** and **T_{hot}** for the engine compartment fluids are listed in Tables B-3-9 to B-3-14.

3.5 Heat Capacity of the Engine Compartment Fluids and Their Vapors

The heat capacity[2] values of the engine compartment fluids and their vapors were determined by two different methods [8, 10]. For the fluids, the values were determined from the average mean boiling points and the API gravity following the ASTM D2890-92 Standard Test Method, briefly described in Appendix C-1 [7, 8]. The heat capacities of the vapors of the engine compartment fluids were determined by using the MDSC following the ASTM E1269-95 Standard Test Method, also described in Appendix B-1 [7, 10].

The heat capacities of the engine compartment fluids and their vapors, determined from the two ASTM Standards Test Methods are listed in Tables B-3-15 and B-3-16 respectively. Heat capacities of other fluids are available in the literature, which are listed in Tables in Appendix B-2-3, B-2-5, B-2-7, and B-2-9 in Appendix B-2.

---

[2] Heat capacity is the quantity of heat required to increase the temperature of a system or substance one degree of temperature [23].

3.6 Heat of Combustion

Heat of combustion defined as the energy released in the combustion of a unit mass of a fluid and has four components:

1) Heat of Complete Combustion (**ΔH_T**): it is defined as the energy released in the complete combustion of a unit mass of a fluid. It is expressed as gross heat of complete combustion when water, which is one of the combustion products, is present in the form of a liquid and as the net heat of complete combustion, when water is present as a vapor[3]. Maxwell [24] has listed both gross and net heat of complete combustion for hydrocarbons, alcohols, glycols and glycerols, ethers, aldehydes, and ketones. Maxwell's data show that the net heat of complete combustion ≈ 0.9274 x gross heat of complete combustion with a standard deviation of 0.0438.
2) Chemical or Actual or Effective Heat of Combustion (**ΔH_{ch}**): it is defined as the energy released in the actual combustion of a unit mass of a fluid. Its value is always less than the **ΔH_T** value. The ratio **$\Delta H_{ch}/\Delta H_T$** is defined as the combustion efficiency (χ) of the fluid.
3) Convective heat of combustion (**ΔH_{con}**): it is defined as the fraction of **ΔH_{ch}** that is carried away from the combustion zone by the flow of hot product-air mixture. The ratio **$\Delta H_{con}/\Delta H_T$** is defined as the convective component of the combustion efficiency (χ_{con});
4) Radiative heat of combustion (**ΔH_{rad}**): it is defined as the fraction of **ΔH_{ch}** that is radiative away from the combustion zone. The ratio **$\Delta H_{rad}/\Delta H_T$** is defined as the radiative component of the combustion efficiency (χ_{rad}). The following relationship has been found between χ and χ_{rad} , which depends on the type of atoms and nature of chemical bonds in the fuel structure [20]:

$$\chi_{rad} = -2.88\chi^3 + 3.56\chi^2 - 0.510\chi - 0.002 \tag{1}$$

---

[3] If the percentage of hydrogen atoms in the sample is known: net heat of complete combustion in MJ/kg = gross heat of complete combustion in MJ/kg – 0.2122 x mass percent of hydrogen atoms, where heat of combustion is in MJ/kg [7]. If the percentage of hydrogen atoms in aviation gasoline and turbine fuel samples is not known: net heat complete of complete combustion in MJ/kg = 10.025 + (0.7195) x gross heat of combustion in MJ/kg [7].

The **ΔH_T** values for the engine compartment fluids were determined by FM Global using the ASTM D240-92 Standard Test Method, described briefly in Appendix B-1. The **ΔH_{ch}** and **ΔH_{con}** values were determined by FM Global using the ASTM E2058 Standard Test Method also described briefly in Appendix B-1. For the determination of the **ΔH_{ch}** and **ΔH_{con}** values, chemical and convective heat release rates were measured along with the release rate of the fluid vapors. Total mass of the fluids burned was also measured directly. The release rates of fluid vapors and chemical and convective heats were integrated. The **ΔH_{ch}** and **ΔH_{con}** values were then calculated from the ratios of the integrated values of respective heat release rates to the integrated value of the release rate of fluid vapors or by the total mass of the fluid burned.

The **ΔH_{rad}** values were calculated from the difference between **ΔH_{ch}** and **ΔH_{con}**. All these values for the engine compartment fluids are listed in Table B-3-18. The average values of the heats of combustion for similar group of engine compartment fluids are listed in Table 2-6 in Chapter II.

3.7 Yields of Products

The yields of products were determined by FM Global using the ASTM E2058 Standard Test Method described briefly in Appendix B-1. The yields were determined from the integrated values of the release rates of the products divided by the integrated value of the release rate of the fluid vapors or by the total mass of the fluids burned.

All yields of products in the combustion of the engine compartment fluids obtained in the ASTM E2058 Method are listed in Table B-3-18. The average yields of products for similar group of engine compartment fluids are listed in Table 2-6 in Chapter II.

Table B-3-4. Distillation Data for the Non-Hydrocarbon Based Engine Compartment Fluids by the ASTM D 86-96 Method [11]

% Distillation	Brake Fluids			Windshield Washing Fluids		Antifreeze		Engine Coolant		
	B10FF									
	011	012	013	019	020	021	022	035	036	050
	New			New		New		New		Used
	Temperature (^{o}C)									
T_{ib}	261	238	238	74	73	149	145	100	101	101
5	266	241	241	80	78	182	166	102	102	102
10	268	243	243	81	79	189	178	103	103	103
20	271	247	246	83	81	191	181	104	105	108
30	273	248	248	86	83	192	182	108	105	112
40	275	252	252	90	86	192	182	115	110	113
50	278	256	256	95	90	192	182	138	129	116
60	281	263	261	98	96	192	182	189	180	117
70	285	273	272	99	99	193	182	191	182	118
80	293	290	288	99	99	193	182	192	182	140
90	316	312	312	99	101	197	182	192	182	193
95	324	324	324		103	205	186	194	182	194
T_{fb}	327	329	334	99	184	205	186	198	183	206

Table B-3-5 Distillation Data for Motor Oils by the ASTM D 2887-97 Method (UEC) [11]

Distillation %	B10FF													
	01	02	03	04	05	06	023	024	027	028	029	030	031	038
	New						Used							
	Temperature (^{o}C)													
T_{ib}	302	287	282	304	303	280	169	111	149	139	145	152	159	213
1	321	303	300	323	323	316	198	119	206	168	175	192	191	253
2	334	320	316	337	340	337	229	147	299	206	216	232	230	321
3	342	330	326	344	349	346	252	163	336	241	252	249	277	339
4	347	338	333	349	355	351	286	169	348	319	317	340	318	349
5	351	343	339	352	360	354	312	176	354	339	344	349	338	355
6	354	347	344	355	363	358	329	185	358	349	354	355	348	360
7	357	351	348	358	367	361	340	192	362	354	358	356	354	363
8	359	354	352	360	369	363	346	200	364	358	362	367	359	367
9	362	357	355	362	372	363	351	206	367	361	364	364	362	369
10	363	359	358	363	374	366	355	212	369	364	367	366	365	372
11	366	362	361	365	376	368	358	223	371	366	369	368	367	374
12	367	364	363	367	378	369	361	229	372	368	371	370	369	377
13	369	366	366	368	380	371	363	241	374	369	372	371	371	378
14	371	368	368	369	382	372	365	287	376	371	373	373	373	380
15	372	369	369	371	383	373	367	326	377	372	375	374	375	382
16	373	371	372	372	385	374	369	338	378	374	376	376	376	383

Table B-3-5 continuing on the next page

Table B-3-5 continued from the previous page

Distillation %	B10FF													
	01	02	03	04	05	06	023	024	027	028	029	030	031	038
	New						Used							
	Temperature (^oC)													
17	374	373	373	373	386	376	371	344	379	375	378	377	378	385
18	376	374	375	374	388	377	372	349	381	376	379	378	379	387
19	377	376	377	376	389	378	374	353	382	377	380	379	381	388
20	378	377	378	377	391	379	376	356	383	378	381	380	382	389
21	379	379	380	378	392	379	377	358	384	380	382	381	383	391
22	381	380	382	379	393	381	378	360	386	381	383	382	384	392
23	382	382	383	380	394	382	380	362	387	382	384	383	386	393
24	383	383	384	381	396	383	381	363	388	383	386	384	387	394
25	384	384	386	382	397	383	383	365	389	384	386	386	388	396
26	386	385	387	383	398	384	384	367	390	385	387	387	389	397
27	387	386	388	384	400	386	386	368	391	386	388	387	390	398
28	388	388	389	385	401	386	387	369	392	387	389	388	391	399
29	389	389	391	386	402	387	388	371	393	388	391	389	392	400
30	390	390	392	387	403	388	389	372	394	389	391	391	393	401
31	391	391	393	388	404	389	391	374	395	389	392	391	394	402
32	392	392	394	389	406	390	392	375	396	391	393	392	395	403
33	393	393	396	390	407	391	393	376	397	392	394	393	396	404
34	394	394	397	391	408	392	394	377	398	393	395	394	397	405
35	395	396	398	392	409	392	396	378	399	393	396	395	398	406
36	396	397	398	393	411	393	397	379	399	394	397	396	399	407
37	397	397	399	394	412	394	398	381	401	395	398	397	400	408
38	398	398	401	395	413	395	399	382	402	396	399	398	401	409
39	399	399	402	396	414	396	401	383	402	397	399	399	402	410
40	400	401	403	397	415	397	402	384	403	398	401	399	403	411
41	401	402	404	398	416	397	403	385	404	398	402	401	404	412
42	402	402	405	399	417	398	405	386	405	399	402	401	405	413
43	403	403	406	399	418	399	406	387	406	400	403	402	406	414
44	404	404	407	401	419	400	407	388	407	401	404	403	407	415
45	405	406	408	402	420	401	408	389	408	402	405	404	408	416
46	406	406	409	403	421	402	410	390	409	403	406	405	408	417
47	407	407	409	404	422	402	411	391	409	403	407	406	409	418
48	408	408	411	404	423	403	412	392	411	404	407	407	411	418
49	409	409	412	406	424	404	413	393	411	405	408	407	411	419
50	410	410	412	407	425	405	415	394	412	406	409	408	412	420
51	411	411	413	413	426	406	416	396	413	407	410	409	413	421
52	412	412	414	408	427	407	417	396	414	408	411	410	414	422
53	413	413	415	409	428	407	418	397	415	408	412	411	415	423
54	414	413	416	411	429	408	420	398	416	409	413	412	416	424
55	415	414	417	412	431	409	421	399	417	410	414	413	417	424

Table B-3-5 continuing on the next page

Table B-3-5 continued from the previous page

Distillation %	B10FF													
	01	02	03	04	05	06	023	024	027	028	029	030	031	038
	New						Used							
	Temperature (^{o}C)													
56	416	416	418	413	432	410	422	401	417	411	414	414	418	426
57	417	416	419	414	433	411	424	402	418	412	416	414	419	427
58	418	417	419	415	434	412	425	402	419	412	416	416	419	427
59	419	418	421	416	435	412	426	403	420	413	417	416	421	428
60	420	419	422	417	436	413	428	404	421	414	418	417	422	429
61	421	419	422	418	437	414	429	406	422	415	419	418	422	431
62	422	421	423	419	438	415	430	407	423	416	420	419	423	431
63	423	421	424	420	439	416	432	408	423	416	421	420	424	432
64	424	422	425	421	440	417	433	409	424	417	422	421	425	433
65	424	423	426	422	441	417	434	410	426	418	423	422	426	434
66	426	424	427	423	442	418	436	411	427	419	423	423	427	435
67	427	425	428	424	443	419	437	412	427	419	424	423	428	436
68	428	426	429	426	444	420	438	413	428	421	426	424	429	437
69	429	427	430	427	446	421	440	414	429	421	427	426	431	438
70	430	428	431	428	447	422	441	415	430	422	427	426	432	439
71	431	428	432	429	448	422	443	416	431	423	428	427	433	441
72	432	429	433	431	449	423	444	417	432	424	429	428	434	442
73	433	430	434	432	451	424	446	418	433	424	431	429	435	443
74	434	431	435	434	452	425	447	419	434	426	432	431	436	444
75	436	432	436	436	453	426	449	421	436	427	433	431	437	445
76	437	433	437	437	454	427	451	422	437	427	434	432	439	446
77	438	434	438	438	455	428	452	423	438	428	435	433	440	448
78	439	435	439	440	456	429	454	424	439	429	436	434	442	449
79	441	436	441	442	457	430	456	426	440	431	438	436	443	450
80	442	437	442	443	458	431	457	427	441	431	439	437	444	452
81	443	438	443	445	460	432	459	428	443	432	440	438	446	453
82	444	439	445	447	461	433	461	429	444	433	442	439	448	454
83	446	441	446	449	462	434	462	431	446	435	443	441	449	456
84	447	442	448	451	464	436	464	432	447	436	444	442	452	457
85	449	443	449	451	466	437	466	434	448	437	446	444	453	459
86	451	444	451	456	467	438	468	436	450	439	448	445	456	461
87	452	446	453	458	468	439	470	437	452	440	449	447	458	462
88	454	448	454	461	469	441	472	439	453	442	451	448	460	464
89	456	449	457	463	471	442	474	441	456	443	453	451	462	466
90	458	451	459	466	473	444	477	443	458	446	456	452	465	468
91	460	453	461	469	475	446	479	446	460	448	458	454	468	471
92	463	455	464	473	477	447	482	448	463	450	461	457	471	473
93	465	457	467	477	479	449	485	451	466	453	464	459	474	476
94	468	460	471	481	481	452	488	454	469	456	468	463	478	479
95	471	463	474	486	484	454	491	458	473	460	472	467	482	483

Table B-3-5 continuing on the next page

Table B-3-5 continued from the previous page

Distillation %	B10FF													
	01	**02**	**03**	**04**	**05**	**06**	**023**	**024**	**027**	**028**	**029**	**030**	**031**	**038**
	New						**Used**							
	Temperature (^oC)													
96	475	467	479	492	487	457	495	463	478	464	478	473	486	487
97	479	472	485	498	491	461	499	469	484	471	484	481	492	492
98	486	479	493	506	496	466	505	478	493	479	493	491	499	499
99	494	490	504	516	504	475	514	493	507	492	504	505	510	512
T_{fb}	502	499	514	524	511	485	522	506	519	503	512	516	520	524

Table B-3-6. Distillation Data for Synthetic Motor Oils and Lubrication, Power Steering and Transmission Fluids by the ASTM D 2887-97 Method [11]

% Distill	Synthetic Motor Oils					Lubrication	Power Steering Fluids					Transmission		
	B10FF													
	07	**08**	**09**	**032**	**033**	**010**	**014**	**015**	**016**	**051**	**053**	**017**	**018**	**034**
	New			**Used**		**New**	**New**			**Used**		**New**		**Used**
	Temperature (^oC)													
T_{ib}	293	267	236	148	148	124	310	301	298	252	259	241	281	269
1	326	300	302	219	212	196	327	319	317	267	284	258	291	291
2	351	325	343	319	253	230	339	335	331	281	303	275	301	310
3	366	337	358	359	279	274	346	342	339	290	312	286	306	323
4	378	344	367	371	352	320	351	347	344	296	318	293	311	332
5	394	349	372	378	371	353	354	350	349	302	323	299	314	339
6	401	354	377	382	386	372	356	353	352	305	327	304	316	345
7	407	357	381	386	397	385	359	355	356	309	330	308	319	349
8	409	360	384	389	406	397	361	357	358	312	333	313	321	354
9	412	363	387	391	416	407	363	359	361	316	336	316	323	357
10	413	365	390	393	423	416	364	361	364	318	338	319	325	360
11	414	367	392	396	429	423	366	363	366	322	341	322	327	363
12	416	369	394	398	432	429	368	364	368	325	343	326	328	366
13	417	371	397	399	435	436	369	366	371	328	345	328	330	368
14	418	373	399	401	437	441	371	367	373	331	347	331	332	370
15	419	375	401	403	438	446	372	368	374	334	349	333	333	372
16	420	377	403	404	439	449	373	369	376	337	351	336	334	373
17	421	378	404	406	441	453	374	371	378	341	352	338	336	375
18	421	379	406	407	441	456	374	372	380	343	354	339	337	377
19	422	381	408	409	442	459	377	373	382	346	356	342	338	378
20	423	383	409	410	443	462	378	374	383	348	357	343	339	380
21	423	384	411	412	444	465	379	375	385	351	359	345	341	382
22	424	386	412	413	444	467	380	376	387	353	360	347	342	383

Table B-3-6 continuing on the next page

Table B-3-6 continued from the previous page

% Distill	B10FF													
	Synthetic Motor Oils					Lubrication	Power Steering Fluids					Transmission Fluids		
	07	08	09	032	033	010	014	015	016	051	053	017	018	034
	New			Used		New	New			Used		New		Used
	Temperature (^oC)													
23	425	387	414	414	446	469	381	377	388	356	362	348	343	384
24	426	388	415	415	446	472	382	378	390	358	363	350	344	386
25	427	389	417	416	447	473	384	379	392	360	365	352	345	387
26	427	391	418	417	448	476	385	380	393	362	367	353	346	388
27	428	392	419	418	449	477	386	381	395	364	368	354	347	389
28	429	393	421	419	450	479	387	382	397	366	370	356	348	391
29	430	394	422	421	451	481	388	383	398	368	372	357	349	392
30	431	396	423	422	452	482	389	384	400	369	373	358	350	393
31	432	397	424	423	452	483	390	385	402	371	375	359	351	394
32	432	398	426	423	453	485	391	386	403	373	377	360	352	396
33	433	399	427	424	453	486	392	387	404	374	378	361	353	397
34	435	400	428	426	455	488	393	388	406	376	380	362	354	398
35	437	401	429	427	456	489	394	388	408	378	382	363	354	399
36	439	402	431	428	458	490	395	389	409	379	384	364	356	400
37	441	403	432	429	461	491	396	391	411	381	386	366	357	401
38	442	404	433	429	464	492	397	391	413	383	388	367	357	402
39	444	406	434	431	467	493	398	392	414	384	390	368	358	403
40	446	407	435	432	469	495	399	393	416	386	392	369	359	404
41	448	408	437	433	475	496	400	394	418	388	394	370	360	406
42	451	409	438	433	479	497	401	395	419	389	397	371	361	407
43	453	410	439	434	481	498	402	396	421	391	399	372	362	408
44	456	411	440	435	482	499	403	397	423	393	402	373	363	409
45	458	412	441	436	483	500	404	398	426	394	404	374	364	410
46	459	413	442	437	486	501	406	399	427	396	407	375	364	411
47	461	414	443	438	489	502	407	399	429	397	410	376	366	412
48	462	415	444	438	493	503	408	401	432	399	412	377	366	413
49	462	416	446	439	495	504	408	402	434	401	414	378	367	414
50	464	417	447	440	497	505	409	403	437	402	416	379	368	416
51	467	418	448	441	497	506	411	403	440	404	417	380	369	417
52	469	419	449	442	498	507	412	404	443	405	418	381	370	418
53	472	420	451	443	498	508	413	406	447	407	420	382	371	419
54	473	421	452	444	499	509	414	407	450	408	421	383	372	420
55	474	422	453	445	499	510	415	407	453	410	421	384	373	421
56	475	422	454	446	500	511	416	408	457	412	422	385	374	422
57	476	423	455	447	501	512	417	409	461	413	423	386	375	423
58	477	424	456	448	502	513	418	411	464	414	423	387	376	424
59	477	425	457	449	502	514	419	411	468	416	423	388	377	426
60	478	426	459	450	503	515	419	412	472	418	424	389	378	427

Table B-3-6 continuing on the next page

Table B-3-6 continued from the previous page

% Distill	B10FF													
	Synthetic Motor Oils					Lubri cation	Power Steering Fluids					Transmission Fluids		
	07	08	09	032	033	010	014	015	016	051	053	017	018	034
	New			Used		New	New			Used		New		Used
	Temperature (^oC)													
61	478	427	460	452	504	516	421	413	475	419	424	391	379	428
62	479	428	461	453	505	517	422	414	478	421	425	392	380	429
63	481	429	462	455	506	518	422	416	481	422	425	393	381	431
64	482	430	463	457	506	519	423	417	484	424	426	394	382	432
65	483	431	465	459	507	520	424	417	486	426	426	395	383	433
66	484	432	466	462	508	521	425	418	489	427	426	396	384	434
67	486	433	467	464	508	522	426	419	492	428	427	397	386	436
68	487	434	469	467	509	523	427	421	494	430	427	399	387	437
69	487	435	470	469	509	524	427	422	496	432	427	400	389	438
70	488	437	472	472	510	526	428	423	498	434	428	402	390	440
72	490	439	474	477	511	527	430	425	502	437	428	404	393	443
73	491	441	476	479	512	528	431	427	504	439	429	406	395	444
74	491	443	477	481	512	529	432	428	506	441	429	407	397	446
75	492	445	478	484	513	531	433	429	508	443	430	408	399	447
77	493	449	482	489	513	533	434	432	512	448	431	411	403	450
78	495	453	483	492	514	534	436	433	513	451	432	413	405	452
79	496	456	485	493	514	536	437	434	515	453	433	414	407	453
80	498	459	487	494	515	537	438	436	517	457	433	416	409	454
81	499	462	488	496	516	538	440	437	519	460	434	418	412	456
82	500	464	490	498	518	539	442	439	521	464	434	419	414	458
83	502	467	492	499	519	541	443	441	523	468	435	421	417	459
84	503	471	494	501	522	542	445	442	524	473	436	423	419	462
85	504	476	496	502	523	544	447	444	527	478	436	425	422	463
86	506	479	498	503	526	546	449	446	528	483	437	427	424	466
87	509	481	500	504	531	547	452	448	531	486	439	429	427	467
88	511	483	502	505	537	549	454	450	533	492	441	432	431	469
89	513	485	505	506	541	551	457	452	535	498	444	434	434	472
90	516	487	507	508	544	552	459	454	537	504	449	437	437	474
91	520	489	510	509	546	554	463	457	539	511	455	440	441	477
92	523	492	513	512	548	557	466	461	542	517	463	443	445	480
93	527	497	516	516	549	559	471	464	545	523	472	447	449	483
94	530	504	520	520	551	562	475	468	548	529	477	451	454	487
95	533	513	524	528	553	566	480	472	551	536	481	455	458	491
96	537	521	528	536	556	571	484	478	555	543	484	460	464	496
97	542	527	533	542	559	578	489	484	560	551	487	467	471	502
98	548	533	539	547	564	588	496	494	567	560	491	476	481	509
99	557	544	549	554	581	606	509	507	578	573	506	490	493	521
T_{fb}	564	554	556	562	591	622	521	519	590	584	524	502	504	531

Table B-3-7. Distillation Data for the Hydrocarbon-Based Engine Compartment Fluids by the ASTM D 2887-97 Test Method (GM) [8]

Fluid	New/ Used	Distillation (%)										
		0.50	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**99.50**
		Temperature (°C)										
		Motor Oils										
B10FF001	**New, Petroleum**	341	365	375	385	393	401	410	419	428	441	473
B10FF002		305	362	377	388	398	407	416	425	436	454	513
B10FF003		299	362	378	389	399	408	417	427	439	457	472
B10FF004		333	394	376	385	395	404	414	427	442	462	513
B10FF005		313	381	398	410	421	431	440	450	460	472	509
B10FF006		50	369	380	390	398	407	415	424	434	450	513
B10FF007	**New, Synthetic**	373	413	421	431	446	458	472	479	488	498	519
B10FF008		244	370	385	396	407	417	428	440	454	469	507
B10FF009		123	374	395	410	423	436	450	462	475	493	522
B10FF023	**Used, Petroleum**	182	354	371	386	399	414	429	444	460	477	515
B10FF024		109	331	359	370	380	390	400	412	424	440	485
B10FF025		135	367	383	396	408	420	433	446	460	476	515
B10FF026		<24	382	395	402	409	415	422	432	445	469	485
B10FF027		136	357	375	389	402	416	430	446	462	484	522
B10FF028		138	364	376	385	394	404	414	423	434	448	497
B10FF029		169	373	382	391	399	408	417	426	435	448	467
B10FF030		228	373	383	392	399	407	415	423	432	443	486
B10FF031		226	378	391	398	405	412	419	426	435	451	500
B10FF037		158	364	378	389	399	410	420	431	443	458	516
B10FF038		66	367	382	394	405	416	427	438	451	465	513

Table B-3-7 continuing on the next page

Table B-3-7 continued from the previous page

Fluid	New/ Used	Distillation (%)										
		0.50	10	20	30	40	50	60	70	80	90	99.50
		Temperature (^oC)										
		Motor Oils										
B10FF039	Used, Petroleum	143	359	378	390	401	411	422	433	445	459	500
B10FF041		177	374	393	406	417	327	437	448	459	475	520
B10FF042		139	384	398	408	417	426	434	444	457	476	518
B10FF043		137	364	379	387	395	402	410	418	427	444	509
B10FF044		192	376	391	403	415	427	439	451	462	475	521
B10FF045		175	388	403	417	429	442	455	466	478	493	522
B10FF046		176	383	395	405	415	425	435	445		469	520
B10FF032	Used, Synthetic	110	381	397	409	418	428	445	463	476	487	516
B10FF033		77	411	418	424	448	467	473	480	486	491	513
B10FF040		167	377	394	407	418	428	443	469	479	441	500
B10FF047		135	388	406	418	429	439	451	463	478	495	521
B10FF048		175	423	430	438	460	484	499	496	500	505	519
		Gear Lubrication Fluid										
B10FF010	New	54	397	434	452	464	475	485	494	504	515	524
		Power Steering Fluids										
B10FF014	New	348	378	388	396	405	412	420	428	441	467	515
B10FF015		345	373	382	389	396	402	408	415	424	438	507
B10FF016		309	354	372	388	403	420	442	465	485	504	523
B10FF051	Used	239	345	376	396	412	426	439	454	469	495	523
		Automatic Transmission Fluids										
B10FF017	New	239	315	339	354	366	378	390	405	423	451	515
B10FF018		242	319	333	344	353	363	373	387	408	439	516
B10FF034	Used	279	351	365	376	384	393	403	413	425	441	500

Table B-3-8. Vaporization Data for Engine Compartment Fluids from MDSC [10]

Fluid	New/ Used	Vaporization Temperature Range (°C)		$T_{v,peak}$ (°C)	E_v (kJ/g)
		Initial	Final		
Motor Oils					
B10FF001	**New, Petroleum**	210	307	271	0.179
B10FF002		203	308	275	0.196
B10FF003		116	318	264	0.215
B10FF004		116	312	235	0.215
B10FF005		181	335	284	0.098
B10FF006		192	310	271	0.145
B10FF007	**New, Synthetic**	220	336	299	0.130
B10FF008		141	313	255	0.110
B10FF009		237	342	310	0.117
B10FF023	**Used, Petroleum**	304	348	335	0.118
B10FF024		323	360	346	0.070
B10FF025		273	322	298	0.120
B10FF026		310	324	316	0.085
B10FF027		292	356	325	0.087
B10FF028		318	365	344	0.125
B10FF029		338	365	354	0.083
B10FF030		295	385	345	0.145
B10FF031		286	355	326	0.133
B10FF037		297	379	355	0.106
B10FF038		346	396	380	0.107
B10FF039		294	366	349	0.123
B10FF040		298	381	350	0.125
B10FF041		323	392	373	0.145
B10FF042		336	390	371	0.091
B10FF043		305	376	343	0.077
B10FF044		333	393	373	0.119
B10FF045		296	367	332	0.142
B10FF046		333	393	367	0.111
B10FF032	**Used, Synthetic**	287	344	312	0.114
B10FF033		362	378	366	0.082
B10FF047		299	385	353	0.168
B10FF048		346	391	375	0.061
Gear Lubrication Fluid					
B10FF010	**New**	201	290	255	0.031
Brake Fluids					
B10FF011	**New**	276	361	320	0.362
B10FF012		178	266	233	0.315
B10FF013		172	263	245	0.282
B10FF052	**Used**	134	239	214	0.199

Table B-3-8 continuing on the next page

Table B-3-8 continued from the previous page

Fluid	New/ Used	Vaporization Temperature Range (°C)		$T_{v,peak}$ (°C)	E_v (kJ/g)
		Initial	Final		
Power Steering Fluids					
B10FF014	**New**	171	307	249	0.164
B10FF015		161	294	248	0.171
B10FF016		144	299	235	0.136
B10FF051	**Used**	378	431	399	0.094
Automatic Transmission Fluids					
B10FF017	**New**	229	322	309	0.201
B10FF018		204	289	273	0.193
B10FF034	**Used**	266	330	318	0.133
Antifreeze					
B10FF021	**New**	126	217	207	0.610
B10FF022		161	225	195	0.484
Engine Coolants					
B10FF035	**New**	210	253	218	1.130
B10FF036		211	246	220	1.048
B10FF049	**Used**	156	217	185	0.985
B10FF050		203	259	226	1.081
Windshield Washing Fluids					
B10FF019	**New**	192	222	198	0.534
B10FF020		181	218	193	1.339

Table B-3-9 Flash Points and Autoignition Temperatures of Engine Compartment Fluids [11]

Fluid	New/ Used	Temperature (°C)	
		Flash-Point (D93)	Autoignition (E659)
Motor Oils			
B10FF001	**New, Petroleum**	188	353
B10FF002		188	343
B10FF003		185	344
B10FF004		193	349
B10FF005		188	357
B10FF006		177	357
B10FF007	**New, Synthetic**	199	364
B10FF008		182	356
B10FF009		182	>382
B10FF023	**Used, Petroleum**	135	>382
B10FF024		63	>382
B10FF027		152	>382
B10FF028		110	>382

Table B-3-9 continuing on the next page

Table B-3-9 continued from the previous page

Fluid	**New/ Used**	**Temperature (^{o}C)**	
		Flash-Point (D93)	**Autoignition (E659)**
B10FF029	**Used, Petroleum**	110	>382
B10FF030		129	>382
B10FF031		129	>382
B10FF038		224-238	331
B10FF032	**Used, Synthetic**	171	>382
B10FF033		149	>382
Gear Lubrication Fluid			
B10FF010	**New**	154	>382
Power Steering Fluids			
B10FF014	**New**	182	>382
B10FF015		185	>382
B10FF016		196	368
B10FF051	**Used**	196-204	328
B10FF053		199-213	348
Automatic Transmission Fluids			
B10FF017	**New**	177	332
B10FF018		177	334
B10FF034	**Used**	163	>382
Brake Fluids			
B10FF011	**New**	149	329
B10FF012		135	329
B10FF013		135	329
B10FF052	**Used**	104-141	283
Antifreeze			
B10FF021	**New**	124	>382
B10FF022		107	>382
Engine Coolants			
B10FF035	**New**	NI	>382
B10FF036		NI	>382
B10FF049	**Used**		
B10FF050		>110	343
Windshield Washing Fluids			
B10FF019	**New**	33	>382
B10FF020		30	>382

Table B-3-10. Hot Surface Ignition Temperatures for Motor Oils (New) [9]

Test	B10 FF								
	Petroleum Oils						Synthetic Oils		
	001	002	003	004	005	006	007	008	009
	Hot Crucible Surface Temperature for Ignition (^{o}C)								
1	292	300	304	310	312	312	334	308	306
2	304	294	305	292	311	293	339	310	302
3	300	309	314	302	316	310	339	318	310
4	300	310	321	313	329	308	346	319	305
5	311	308	318	308	327	302	351	316	315
6	310	307	302	314	327	307	348	312	310
7	311	306	313	302	311	296	355	315	307
8	310	315	313	313	321	306	353	306	299
9	300	308	312	313	326	309	355	314	304
10	314	310	303	314	318	309	355	308	311
11	298	302	312	309	325	308	356	305	312
12	310	305	308	306	313	313	356	317	304
13	310	303	310	308	329	303	355	322	304
14	316	313	324	303	328	316	355	315	
15		309	309	305	318		355	314	
16		317	305		335		356	314	
17		312					357		
18							341		
19							345		
20							350		
21							339		
22							350		
23							332		
Avg	306	308	311	307	322	307	350	313	307

Table B-3-11. Hot Surface Ignition Temperatures for Motor Oils (Used) [9]

Test	B10FF											
	Petroleum Oils								Synthetic Oils			
	024	027	028	029	030	031	037	041	032	033	040	047
	Hot Crucible Surface Temperature for Ignition (^{o}C)											
1	316	315	309	312	298	313	307	293	318	328	310	317
2	314	315	306	312	306	323	307	309	322	331	308	314
3	319	320	315	316	310	303	313	291	323	334	322	326
4	308	319	307	311	300	320	310	301	320	335	318	327
5	318	318	302	312	320	321	312	315	316	334	308	323
6	320	318	308	314	301	325	308	315	319	336	322	325
7	318	299	302	319	296	323	309	305	320	327	325	319
8	316	309	299	306	307	323	309	315	317	313	299	337
9	313	307	315	319	313	313	310	312	324	323	335	331
10	314	320	317	306	311	318	308	305	326	335	319	330

B-3-11 continuing on the next page

B-3-11 continued from the previous page

Test	**B10FF**											
	Petroleum Oils								**Synthetic Oils**			
	024	**027**	**028**	**029**	**030**	**031**	**037**	**041**	**032**	**033**	**040**	**047**
	Hot Crucible Surface Temperature for Ignition (^{o}C)											
11	319	320		307	309	323	308		309	339	309	335
12	314	310		322	316	310	316		317	324	312	330
13	317	304		304	307	317	314		316	332	314	
14	326	309		311	319	314	317		323	326	316	
15	316			317		308	316		329	340	317	
16						320	313			329	312	
17						323				353		
18						327				344		
19										350		
20										336		
21										342		
22										338		
23										342		
24										339		
25										349		
26										335		
27										324		
28										334		
29										324		
30										348		
Avg	317	313	308	313	308	318	311	306	320	335	315	325

Table B-3-12. Hot Surface Ignition Temperatures for the Lubrication, Power Steering and Automatic Transmission Fluids [9]

Test	**B10FF**											
	Lubr	**Power Steering**								**Transmission**		
	010	**014**	**015**				**016**	**051**	**053**	**017**	**018**	**034**
	New	**New**						**Used**		**New**		**Used**
T_{fluid} (^{o}C)	**25**	**25**	**25**	**50**	**100**	**150**	**25**	**25**	**25**	**25**	**25**	**25**
	Hot Crucible Surface Temperature for Ignition (^{o}C)											
1	325	305	306	297	304	304	305	311	309	301	307	304
2	310	305	308	302	314	307	301	320	315	311	308	304
3	312	312	308	305	303	309	314	320	316	305	306	308
4	323	311	305	305	317	309	305	322	308	310	310	309
5	318	311	309	305	303	317	323	329	312	308	309	311
6	318	311	309	297	314	316	301	317	322	308	311	308

Table B-3-12 continuing on the next page

Table B-3-12 continued from the previous page

Test	**B10FF**											
	Lubr	**Power Steering**								**Transmission**		
	010	**014**	**015**				**016**	**051**	**053**	**017**	**018**	**034**
	New							**Used**		**New**		**Used**
T_{fluid} (^oC)	**25**	**25**	**25**	**50**	**100**	**150**	**25**	**25**	**25**	**25**	**25**	**25**
	Hot Crucible Surface Temperature for Ignition (^oC)											
7	330	320	303	298	318	321	310	325	314	312	309	311
8	327	300	310	304	316	319	308	331	320	312	310	310
9	332	312	311	312	316	311	312	321	322	309	303	305
10	336	316	316	307	311	312	313	314	322	314	315	302
11	327	311	313	308	312	316	323	321	317	310		310
12	323	305	311	311	325	316	313	321	314	320		303
13	325	314	314	315	314	320	320	321	318	317		
14	338	313	309	317	318	318	308	319	325	316		
15	323	312	310	314	316	322	316	335	317	309		
16	327	306	305	311	321		318	326	325	316		
17	331	305	301	311	322		312	322	318			
18	323	313	305	323	315		312	326	320			
19		310	318	320	321		315	325				
20			312	315	319		314	336				
21			320	317	319			329				
22			312		320			333				
23			324					333				
24			314					331				
25			315									
26			326									
27			331									
28			329									
29			328									
30			329									
31			329									
Average	325	310	314	309	315	314	312	325	317	311	309	307

Table B-3-13. Hot Surface Ignition Temperatures for Non-Hydrocarbon-Based Engine Compartment Fluids [9]

Test	B10FF								
	Brake Fluids				**Antifreeze**		**Engine Coolants**		
	New			**Used**	**New**		**New**		**Used**
	011	**012**	**013**	**052**	**021**	**022**	**035**	**036**	**049**
	Hot Crucible Surface Temperature for Ignition (^{o}C)								
1	270 (NI)	266	269	274	483	490	538	503	511
2	270 (NI)	266	274	276	524	437	564	505	496
3	285 (NI)	272	273	274	481	450	533	502	505
4	285 (NI)	267	280	274	520	506	552	490	539
5	285 (NI)	273	279	275	465	506	556	446	532
6	285 (NI)	273	277	280	483	433	565	516	521
7	285 (NI)	274	281	280	485	460	528	471	517
8	290 (NI)	272	279	283	514	514	575	447	515
9	290 (NI)	274	283	285	532	484	578	514	453
10	290 (NI)	274	283	287	555	508	536	464	547
11	295 (NI)	276	284	292	551	515	550	517	534
12	295 (NI)	272	283	290	545	515	573	517	547
13	295 (NI)	278	283	295	537	467	557	441	528
14	300 (NI)	276	285	298	538	430	578	512	517
15	300 (NI)	273	287	300	550	526	581	440	521
16	300 (NI)	280	285	305	515	491	559	454	525
17	300 (NI)	278	290	307	577	484	554	441	548
18	305 (NI)	279	290	305	553	502		433	534
19	305 (NI)	281	290	312	544	507		519	525
20	305 (NI)	280	291	309	538	492		517	515
21	310 (NI)	283	297	326	559	453		427	536
22	315 (NI)	287	298	327	541	513		527	500
23	320 (NI)	284	297	323	567			498	525
24	325 (NI)	286	295	325	578			509	552
25	330 (NI)	286	295	319	477			453	531
26	335 (NI)	284	301	337	582				554
27		287	300	331	551				549
28		295	301	330	567				562
29		292	303	335	569				561
30		297	302	330	555				
31		292	302		553				
32		298	271		501				
33		304	309		549				
34		303	308		502				
35		301	306		574				
36		301	287		622				
37		304	310		596				
38		264	310		524				
39		264	312		563				
40		269	309		613				

B-3-13 continuing on the next page

Table B-3-13 continued from the previous page

Test	B10FF								
	Brake Fluids				Antifreeze		Engine Coolants		
	New	Used	New	New	Used				
	011	012	013	052	021	022	035	036	049
	Hot Crucible Surface Temperature for Ignition (^{o}C)								
41		275	307		503				
42		270	282		583				
43		283	313		568				
44		289	314		562				
45		284	313		659				
46		264	292		564				
47			309		569				
48					542				
49					581				
Average	NI	281	293	303	529	483	557	479	528

Table B-3-14. Hot Surface Ignition Temperatures for Various Engine Compartment Fluids [9]

Air Flow (m/s)	T °C	Ignition	Air Flow (m/s)	T °C	Ignition
Ignition on Hot Cast Iron Hemisphere					
B10FF002 (Motor Oil, New)			**B10FF015 Power Steering Fluid**		
0	325	0/5	0	335	0/5
	340	0/5		340	0/5
	345	0/5		345	3/5
	350	2/5		350	1/5
	355	3/5		355	3/5
	360	5/5		360	5/5
	365	5/5		365	4/5
B10FF007 (Motor Oil, New)				370	5/5
0	360	375		375	5/5
	370	2/5	1.12	350	0/5
	375	3/5		400	0/5
	380	2/5		425	0/5
	385	4/5		430	0/5
	390	2/5		435	2/5
	395	4/5		440	1/5
	400	2/5		450	1/5
	405	2/5		455	4/5
	420	2/5		460	1/5
	425	5/5		465	2/5
	430	5/5		470	5/5
B10FF011 (Brake Fluid)				480	5/5
0	290	0/5	2.24	500	0/5
	295	0/5		550	0/5
	300	2/5		600	0/5
	305	3/5		650	0/5
	310	0/5			
	315	5/5			
	320	5/5			
	325	5/5			
B10FF016 (Power Steering Fluid)					
0	320	0/5			
	330	0/5			
	340	0/5			
	345	0/5			
	350	1/5			
	355	5/5			
	360	4/5			
	365	4/5			
	370	5/5			
	375	5/5			

Table B-3-15. Heat Capacity of Selected Engine Compartment Fluids [8]

B10FF	New / Old	Temperature (°C)													
		25	50	75	100	125	150	175	200	225	250	275	300	350	400
		Heat Capacity (kJ/kg-K)													
Motor Oils															
001	**Petroleum New**	1.96	2.07	2.17	2.28	2.39	2.49	2.60	2.71	2.81	2.92	3.03	3.13	3.34	3.56
002		1.95	2.05	2.16	2.26	2.37	2.48	2.58	2.69	2.79	2.90	3.00	3.11	3.32	3.53
003		1.95	2.05	2.16	2.26	2.37	2.48	2.58	2.69	2.79	2.90	3.00	3.11	3.32	3.53
004		1.95	2.05	2.16	2.26	2.37	2.48	2.58	2.69	2.79	2.90	3.00	3.11	3.32	3.53
005		1.91	2.02	2.12	2.23	2.33	2.44	2.54	2.64	2.75	2.85	2.96	3.06	3.27	3.48
006		1.97	2.08	2.19	2.30	2.40	2.51	2.62	2.72	2.83	2.94	3.04	3.15	3.37	3.58
Average		1.95	2.05	2.16	2.27	2.37	2.48	2.58	2.69	2.79	2.90	3.01	3.11	3.32	3.54
007	**Synthetic New**	2.01	2.12	2.23	2.34	2.44	2.55	2.66	2.77	2.88	2.99	3.10	3.21	3.42	3.64
008		1.94	2.05	2.15	2.26	2.36	2.47	2.57	2.68	2.79	2.89	3.00	3.10	3.31	3.52
009		2.04	2.15	2.26	2.37	2.48	2.59	2.70	2.81	2.92	3.03	3.14	3.25	3.48	3.70
Average		2.00	2.11	2.21	2.32	2.43	2.54	2.64	2.75	2.86	2.97	3.08	3.19	3.40	3.62
023	**Petroleum Used**	1.91	2.02	2.12	2.22	2.33	2.43	2.54	2.64	2.74	2.85	2.95	3.06	3.26	3.47
024		1.93	2.03	2.14	2.24	12.34	2.45	2.55	2.66	2.76	2.87	2.97	3.08	3.29	3.49
025		1.93	2.03	2.14	2.24	2.35	2.45	2.56	2.66	2.77	2.87	2.87	3.08	3.29	3.50
026		1.93	2.03	2.14	2.24	2.35	2.45	2.56	2.66	2.77	2.87	2.98	3.08	3.29	3.50
027		1.89	1.99	2.10	2.20	2.30	2.40	2.51	2.61	2.71	2.82	2.92	3.02	3.23	3.43
028		1.94	2.04	2.15	2.25	2.36	2.46	2.57	2.67	2.78	2.88	2.99	3.09	3.30	3.51
029		1.94	2.04	2.15	2.25	2.36	2.46	2.57	2.67	2.78	2.88	2.99	3.10	3.31	3.52
030		1.94	2.04	2.15	2.26	2.36	2.47	2.57	2.68	2.78	2.89	2.99	3.10	3.31	3.52
031		1.89	1.99	2.10	2.20	2.30	2.41	2.51	2.61	2.72	2.82	2.92	3.02	3.23	3.44

Table B-3-15 continuing on the next page

Table B-3-15 continued from the pervious page

B10FF	New / Old	Temperature (^{o}C)													
		25	50	75	100	125	150	175	200	225	250	275	300	350	400
		Heat Capacity (kJ/kg-K)													
Motor Oils															
037	**Petroleum Used**	1.93	2.03	2.14	2.24	2.35	2.45	2.56							
038		1.93	2.03	2.14	2.24	2.35	2.45	2.56	2.66	2.77	2.87	2.98	3.08	3.29	3.50
039		1.92	2.03	2.13	2.24	2.34	2.45	2.55	2.65	2.76	2.86	2.97	3.07	3.28	3.49
041		1.93	2.04	2.14	2.25	2.46	2.46	2.56	2.67	2.77	2.88	2.98	3.09	3.30	3.51
042		1.93	2.04	2.14	2.25	2.35	2.46	2.56	2.67	2.77	2.88	2.98	3.09	3.30	3 51
043		1.92	2.02	2.13	2.23	2.33	2.44	2.54	2.65	2.75	2.86	2.96	3.06	3.27	3.48
044		1.93	2.04	2.14	2.25	2.35	2.46	2.56	2.67	2.77	2.88	2.98	3.09	3.30	3.51
045		1.94	2.05	2.15	2.26	2.37	2.47	2.58	2.68	2.79	2.89	3.00	3.11	3.32	3.53
046		1.94	2.04	2.15	2.25	2.36	2.47	2.57	2.68	2.78	2.89	2.99	3.10	3.31	3.52
Average		1.93	2.04	2.14	2.24	2.35	2.46	2.59	2.70	2.80	2.89	2.99	3.10	3.31	3.52
032	**Synthetic Used**	1.92	2.03	2.13	2.24	2.34					2.82	2.92	3.02	3.23	3.44
033		1.84	1.94	2.04	2.14	2.24	2.35	2.55	2.66	2.76	2.87	2.97	3.08	3.29	3.49
040		1.93	2.04	2.14	2.25	2.35	2.46	2.56	2.67	2.76	2.88	2.98	3.09	3.30	3.51
047		1.96	2.07	2.17	2.28	2.38	2.49	2.60	2.70	2.81	2.92	3.02	3.13	3.34	3.55
048		1.99	2.10	2.21	2.31	2.42	2.53	2.64	2.75	2.85	2.96	3.07	3.18	3.39	3.61
Average		2.37	2.03	2.14	2.24	2.79	2.45	2.56	2.66	2.77	2.87	2.97	3.08	3.29	3.50
Gear Lubrication Fluid															
010	**New**	1.91	2.02	2.12	2.22	2.33	2.43	2.54	2.64	2.75	2.85	2.95	3.06	3.27	3.48

Table B-3-15 continuing on the next page

Table B-3-15 continued from the previous page

B10FF	**New / Old**	**Temperature (^{o}C)**													
		25	**50**	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**275**	**300**	**350**	**400**
		Heat Capacity (kJ/kg-K)													
Power Steering Fluids															
014	**New**	1.98	2.09	2.20	2.30	2.41	2.52	2.63	2.73	2.84	2.95	3.05	3.16	3.38	3.59
015		1.96	2.07	2.18	2.28	2.39	2.49	2.60	2.71	2.81	2.92	3.03	3.13	3.35	3.56
016		1.96	2.07	2.17	2.28	2.36	2.49	2.60	2.70	2.81	2.92	3.02	3.13	3.34	3.55
Average		1.97	2.08	2.18	2.29	2.39	2.50	2.61	2.71	2.82	2.93	3.03	3.14	3.36	3.57
051	**Used**	1.94	2.05	2.15	2.26	2.37	2.47	2.58	2.68	2.79	2.89	3.00	3.11	3.32	3.53
Automatic Transmission Fluids															
017	**New**	1.94	2.04	2.15	2.25	2.36	2.46	2.57	2.67	2.78	2.88	2.99	3.09	3.30	3.51
018		1.93	2.04	2.14	2.25	2.35	2.46	2.56	2.66	2.77	2.87	2.98	3.08	3.29	3.50
Average		1.94	2.04	2.15	2.25	2.36	2.46	2.57	2.67	2.78	2.88	2.99	3.09	3.30	3.51
034	**Used**	1.95	2.05	2.16	2.26	2.37	2.48	2.56	2.60	2.70	2.74	2.86	2.95	3.32	3.35
Engine Coolant															
035	**New**										2.90	3.00	3.11	3.32	3.53

Table B-3-16. Heat Capacity of Vapors and Heat of Vaporization of Engine Compartment Fluids [10]

Fluid Type	Fluid (B10FF)	Vaporization Range (°C)	Temperature (°C)						ΔH_v (kJ/g)
			25	65	105	145	185	225	
			Heat Capacity of Vapors (kJ/kg-K)						
Motor Oils									
New Petroleum	001	210-307	1.88	2.03	2.18	2.31	2.44	2.44	0.527
	002	203-308	1.46	1.59	1.72	1.83	1.91	1.92	0.456
	003	116-318	1.13	1.24	1.34	1.42	1.44	1.37	0.318
	004	116-312	1.65	1.78	1.89	1.96	1.94	1.57	0.365
	005	181-335	1.45	1.57	1.68	1.77	1.84	1.86	0.324
	006	192-465	1.59	1.73	1.85	1.95	2.02	2.04	0.411
	Average		1.53	1.66	1.78	1.87	1.93	1.87	0.400
New Synthetic	007	220-336	1.41	1.52	1.61	1.69	1.77	1.98	0.405
	008	141-313	1.25	1.38	1.50	1.59	1.62	1.54	0.255
	009	237-342	1.56	1.70	1.82	1.93	2.00	2.02	0.448
	Average		1.41	1.53	1.64	1.74	1.80	1.85	0.369
Used Petroleum	023	304-348	1.71	1.90	2.10	2.28	2.32	2.19	0.595
	024	323-360	1.73	1.92	2.04	2.12	1.96	1.68	0.586
	025	273-322	1.58	1.77	1.93	2.05	2.10	2.12	0.512
	026	310-324	1.51	1.71	1.97	2.19	2.21	2.19	0.515
	027	292-356	1.33	1.49	1.63	1.73	1.74	1.85	0.442
	028	318-365	2.18	2.48	2.70	2.89	2.89	2.85	0.764
	029	338-365	1.81	2.03	2.22	2.41	2.36	2.29	0.650
	030	295-568	1.45	1.62	1.76	1.88	1.93	1.96	0.537
	031	286-355	1.40	1.56	1.71	1.83	1.92	1.95	0.498
	037	297-379	1.67	1.78	1.91	2.02	2.12	2.13	0.560
	038	346-396	1.30	1.37	1.44	1.50	1.56	1.60	0.524
	039	294-366	1.59	1.74	1.86	1.98	2.09	2.08	0.551
	041	323-392	1.33	1.46	1.56	1.67	1.74	1.73	0.541
	042	336-390	1.39	1.50	1.60	1.69	1.78	1.80	0.523
	043	305-376	1.60	1.75	1.87	1.97	2.06	2.04	0.525
	044	333-393	1.43	1.55	1.67	1.77	1.87	1.84	0.559
	045	296-367	1.42	1.56	1.68	1.79	1.92	2.02	0.527
	046	333-393	1.42	1.54	1.63	1.72	1.79	1.78	0.548
	Average		1.55	1.71	1.85	1.97	2.02	2.01	0.553

Table B-3-16 continuing on the next page

Table B-3-16 continued from the previous page

Fluid Type	**Fluid (B10FF)**	**Vaporization Range (°C)**	**Temperature (°C)**						**ΔH_v (kJ/g)**
			25	**65**	**105**	**145**	**185**	**225**	
			Heat Capacity of Vapors (kJ/kg-K)						
Motor Oils									
Used, Synthetic	032	287-344	1.41	1.57	1.74	1.86	1.97	2.12	0.483
	033	362-378	1.46	1.61	1.73	1.83	1.93	2.06	0.574
	040	298-381	1.30	1.40	1.50	1.58	1.64	1.66	
	047	299-385	1.53	1.67	1.78	1.87	1.93	1.96	0.587
	048	346-391	1.73	1.84	1.94	2.03	2.09	2.04	0.616
		Average	1.49	1.62	1.74	1.83	1.91	1.97	0.565
Gear Lubrication Fluid									
New	010	201-290	1.44	1.59	1.72	1.83	1.93	1.99	0.284
Power Steering Fluids									
New	014	171-307	1.60	1.75	1.86	1.95	1.94	1.43	0.398
	015	161-294	1.77	1.92	2.00	2.14	2.18	1.97	0.412
	016	144-299	1.42	1.56	1.69	1.78	1.82	1.73	0.305
		Average	1.60	1.74	1.85	1.96	1.98	1.71	0.371
Used	051	378-431	1.41	1.53	1.63	1.71	1.77	1.82	0.592
Automatic Transmission Fluids									
New	017	229-322	1.37	1.51	1.63	1.77	1.83	1.85	0.480
	018	204-289	1.67	1.84	2.01	2.16	2.27	2.25	0.492
		Average	1.52	1.68	1.82	1.97	2.05	2.05	0.486
Brake Fluids									
New	011	276-361	1.37	1.46	1.55	1.61	1.66	1.68	0.706
	012	178-266	1.29	1.39	1.48	1.55	1.60	0.96	0.512
	013	172-263	1.51	1.60	1.71	1.77	1.80	1.56	0.504
		Average	1.39	1.48	1.58	1.64	1.69	1.40	*0.574*
Used	052	134-239	1.63	1.75	1.89	1.93	1.76	0.75	0.377
Antifreeze									
New	021	126-217	1.75	1.92	2.08	2.17	1.94	0.84	0.787
	022	161-225	1.75	1.95	2.14	2.28	2.17	1.88	0.722
		Average	1.75	1.94	2.11	2.23	2.06	1.36	0.754
Engine Coolants									
New	035	210-253	1.98	2.13	2.23	2.43	2.38	2.42	1.496
	036	211-246	1.23	1.39	1.53	1.65	1.79	1.86	1.277
		Average	1.61	1.76	1.88	2.04	2.09	2.14	1.387

Table B-3-16 continuing on the next page

Table B-3-16 continued from the previous page

Fluid Type	**Fluid (B10FF)**	**Vaporization Range (^{o}C)**	**Temperature (^{o}C)**						**ΔH_{vap} (kJ/g)**
			25	**65**	**105**	**145**	**185**	**225**	
			Heat Capacity of Vapors (kJ/kg-K)						
Engine Coolants Continuing									
Used	049	156-217	1.72	1.93	2.00	3.05	2.82	0.16	1.210
	050	203-259	1.84	2.03	2.17	2.31	2.33	3.10	1.409
	Average		1.78	1.98	2.09	2.68	2.58	1.63	1.309
Windshield Washing Fluids									
New	019	192-222	2.54	2.75	2.86	2.20	1.75	0.61	0.958
	020	181-218	2.28	2.45	2.64	2.69	2.92	0.10	1.695
	Average		2.41	2.60	2.75	2.45	2.34	0.36	1.326

Table B-3-17. Lower and Upper Flammability Limits of Selected Engine Compartment Fluids [11]

Fluid	New/ Used	Fluid (B10FF)	Temp Range (°C)	LFL (%)	UFL (%)
Motor Oils (Petroleum)	**New**	001	260-271	0.7 - 1.2	4.2-4.7
		002	240-256	1.3	>5.0
		003	240-243	0.6-1.1	>3.4
		004	215	0.3-0.8	>1.9
		005	270-280	1.0-1.5	4.5-5.0
		006	269-272	1.7-2.2	5.5-6.0
	Used	023	200	1.3	>2.4
		024	200	1.0-1.5	>8.1
		025	250	0.8	4.8
		026	250-260	0.8	4.8
		027	200	1.0-1.5	>8.1
		028	200	0.5-1.0	>1.0
		029	220	0.5-1.0	>3.1
		030	220	0.5-1.0	>1.9
		031	240	0.2-0.7	>5.7
		038	250	0.80	2.6
Motor Oils (Synthetic)	**New**	007	260-264	1.0-1.5	>3.7
		008	261-269	0.8	4.0
		009	275-280	2.5-3.0	6.0-6.5
	Used	032	275	2.9-3.4	7.3-7.8
		033	275	1.9-2.3	>3.2
Gear Lubrication Fluid	**New**	010	270-280	0.8	3.15
Power Steering fluids	**New**	014	208-216	0.5-1.0	>1.3
		015	210-212	1.0	>1.0
	Used	051	250	1.0	>3.8
		053	250	0.8	2.6
Automatic Transmission Fluids	**New**	017	225-227	0.8	>1.9
		018	225-226	1.0	>2.6
	Used	034	265-275	1.0-1.4	>2.4
New Brake Fluids	**New**	011	245-250	4.5-5.0	15.3-16.3
		012	244-248	4.5-5.0	18.4-19.4
		013	245-249	3.5-4.0	12.6-13.6
	Used	052	250	5.3	>9.7
Antifreeze	**New**	021	170	5.0-5.5	30.1-31.1
		022	170	3.8-4.3	18.4-19.4
Engine Coolants	**New**	035	250	12.1	42.0
		036	220	7.2	37.1-37.7
	Used	050	250	13.1	40.5
Windshield Washing Fluids	**Summer**	019	60	18.8-19.8	>34.9
	Winter	020	75	21.1	48.1

Table B-3-18. Heats of Combustion and Yields of Products for the Engine Compartment Fluids [11]

New/Used	Fluid	Measured		Calculated		y_{co}	y_{co2}	y_{hc}	y_{sm}
		ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}				
		kJ/g				g/g			
Motor Oils									
New, Petroleum	B10FF001	42.8	23.0	9.9	13.1	0.012	1.76	0.003	0.036
	B10FF002	43.3	34.2	17.0	17.2	0.025	2.55	0.003	0.038
	B10FF003	43.1	29.3	12.4	16.9	0.021	2.19	0.007	0.062
	B10FF004	43.1	27.5	11.4	16.1	0.018	2.05	<0.001	0.057
	B10FF005	42.6	23.0	9.9	13.1	0.018	1.71	0.001	0.073
	B10FF006	42.0	33.1	16.4	16.7	0.019	2.47	<0.001	0.045
	Average	42.8	28.4	12.8	15.5	0.019	2.12	0.004	0.052
Used, Petroleum	B10FF023	41.3	35.4	20.4	15.0	0.015	2.25	0.010	0.042
	B10FF024	41.1	28.3	12.1	16.2	0.020	2.11	0.001	0.071
	B10FF027	40.2	32.7	17.1	15.6	0.023	2.44	0.001	0.069
	B10FF028	42.4	28.2	11.8	16.4	0.021	2.11	<0.001	0.069
	B10FF029	42.2	28.3	11.9	16.4	0.013	2.12	<0.001	0.052
	B10FF030	42.1	31.1	14.1	17.0	0.022	2.32	<0.001	0.025
	B10FF031	41.7	22.8	9.8	13.0	0.020	1.70	<0.001	0.065
	B10FF038	42.5	37.8	23.6	14.2	0.023	2.82	0.001	0.075
	Average	41.7	30.6	15.1	15.5	0.018	2.23	0.003	0.059
New, Synthetic	B10FF007	40.6	31.5	15.3	16.2	0.014	2.38	0.001	0.049
	B10FF008	41.9	27.6	11.5	16.1	0.023	2.06	<0.001	0.053
	B10FF009	44.4	27.1	11.2	15.9	0.011	2.04	<0.001	0.029
	Average	42.3	28.7	12.7	16.1	0.016	2.16	0.001	0.044
Used, Synthetic	B10FF032	38.3	23.9	9.9	14.0	0.017	1.78	0.001	0.059
	B10FF033	44.0	30.8	13.3	17.5	0.011	2.30	0.001	0.082
	Average	41.2	27.4	11.6	15.8	0.014	2.04	0.001	0.071
Gear Lubrication Fluid									
New	B10FF010	42.7	30.7	13.6	17.1	0.025	2.29	0.003	0.072
Power Steering Fluids									
New	B10FF014	41.4	31.6	15.0	16.6	0.022	2.35	<0.001	0.083
	B10FF015	40.8	19.5	9.2	10.3	0.023	1.45	<0.001	0.059
	B10FF016	43.5	25.1	10.5	14.6	0.017	1.90	0.001	0.049
	Average	41.9	25.4	11.6	13.8	0.021	1.90	0.001	0.064
Used	B10FF051	41.3	30.4	13.8	16.6	0.023	2.27	<0.001	0.077

Table B-3-18 continuing on the next page

Table B-3-18 continued from the previous page

New/Used	Fluid	Measured		Calculated		y_{co}	y_{co2}	y_{hc}	y_{sm}
		ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}				
		kJ/g				g/g			
Automatic Transmission Fluids									
New	B10FF017	43.4	21.5	9.8	11.7	0.019	1.60	<0.001	0.060
	B10FF018	41.8	30.0	13.2	16.8	0.020	2.24	0.002	0.062
	Average	42.6	25.8	11.5	14.3	0.020	1.92	0.002	0.062
Used	B10FF034	42.9	32.4	15.1	17.3	0.024	2.41	0.001	
Brake Fluids									
New	B10FF011	27.1	23.4	13.7	9.7	0.005	1.76	<0.001	<0.001
	B10FF012	25.1	20.2	10.4	9.8	0.003	1.52	<0.001	<0.001
	B10FF013	24.9	22.5	14.6	7.9	0.005	1.69	<0.001	<0.001
	Average	25.7	22.0	12.9	9.1	0.004	1.66	<0.001	<0.001
Used	B10FF052	25.2	23.8	17.1	6.7	0.002	1.79	<0.001	0.007
Antifreeze									
New	B10FF021	18.2	17.6	13.4	4.2	0.007	1.32	<0.001	
	B10FF022	21.5	14.6	6.2	8.4	0.002	1.10	0.001	0.006
	Average	19.9	16.1	9.8	6.3	0.005	1.21	0.001	0.006
Engine Coolants									
New	B10FF035	**No Ignition**							
	B10FF036								
Used	B10FF050								
Windshield Washing Fluids									
New	B10FF019		14.2			0.012	1.10	<0.001	0.019
	B10FF020	16.9	7.6	3.8	3.8	0.003	0.67	<0.001	0.001
	Average	16.9	10.9	3.8	3.8	0.008	0.89	<0.001	0.010