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Ignition of Gases, Vapors, and Liquids by Hot Surfaces

*Vytenis Babrauskas**, *John Jay College of Criminal Justice, New York, NY, USA and Fire Science and Technology Inc, New York, NY, USA*

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Abstract. Gases, vapors, liquid sprays, aerosols and other forms of ignitable fluids dispersed into the atmosphere, under certain circumstances, may encounter a hot surface. When investigating a fire, it may be necessary to determine in such cases if the hot surface was a competent ignition source. The paper reviews the available experimental data and findings on this topic and gives appropriate advice. It is shown that, unlike the autoignition temperature (AIT), which is only slightly dependent on test conditions, the hot-surface ignition temperature (HSIT) is highly dependent on the test environment conditions. The primary variable affecting the outcome is the degree of 'enclosedness.' If the degree of enclosedness is not extreme, a standard recommendation is that the hot-surface ignition temperature might be assumed to be 200°C higher than the AIT. But for conditions of significant enclosedness, the actual ignition temperature is more influenced by the fuel's volatility (which is related to its flash point) than its AIT value. Higher volatility fuels are harder, not easier, to ignite from a hot surface. Since gasoline is the most volatile of the common automotive-use ignitable liquids, it turns out to be the one which is the hardest to ignite by a hot surface. Nonetheless, in some cases, vehicular engine compartment temperatures can become high enough for gasoline to get ignited. When conducting HSIT tests, it is important to be cognizant of the probabilistic nature of the ignition problem.

Keywords: Gasoline, Hot surfaces, Ignitable liquids, Ignition, Motor vehicles, Vapors

1. Introduction

There is a potential for ignition if gases, vapors, liquid sprays, aerosols or other forms of ignitable fluids become dispersed into the atmosphere and encounter a hot surface. Perhaps most commonly, this is encountered in motor vehicles, however, the problem is quite general and can occur in factories, homes (e.g., vapors from a spill igniting on the coils of a radiant heater), and other places. The possibility for this to happen has been known since at least 1815, when Sir Humphry Davy investigated the ignitability of gases by hot metals and concluded that plunging an iron bar "at the highest degree of red heat and at the common degree of white heat" into an atmosphere containing firedamp (mine gases consisting mostly of methane) did not ignite the mixture [1].

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*Correspondence should be addressed to: Vytenis Babrauskas, E-mail: vytob@doctorfire.com

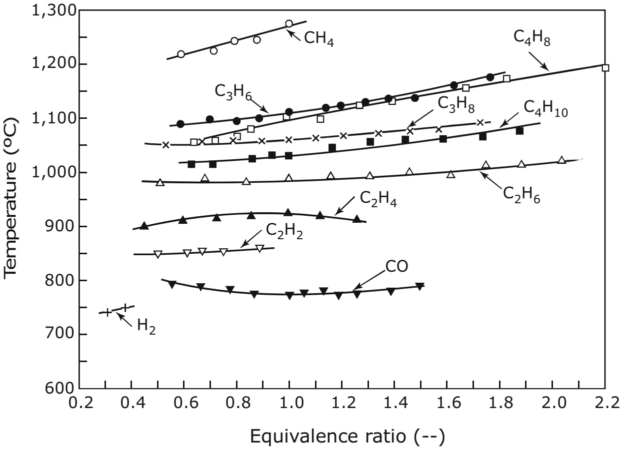

Figure 1. The effect of equivalence ratio on the hot-surface ignitability of some gases (ignition by a 1 mm Nichrome wire) [4].

The first scientists to suggest an explanation for this were the pioneering combustion researchers Mallard and Le Chatelier [2], who in 1880 proposed that while a gas volume directly next to the heated surface does heat up to a high temperature, convective effects quickly sweep it out of that area, where it is cooled down. In other words, they suggested that if the *residence time* of the heated volume of gas is less than the *induction period*,[1] ignition does not occur. By 1927 Coward and Guest [3] succeeded in quantifying what Davy could only examine qualitatively. They found that a metal strip heated to 1000°C–1060°C would ignite natural gas, although they did not develop any engineering trends. A larger data collection was assembled by Vanpée and Bruszak [4], who found that, for many but not all gases, the easiest to ignite mixture using a hot surface for ignition was at the LFL. This is shown in Fig. 1, where the fuel concentration is given as the *equivalence ratio* φ.[2]

Understanding the situation may be helped by considering what happens to an aliquot of fuel which is injected into an environment where a hot surface is present. Assume for simplicity that a single droplet has been injected. Initially, the vapors surrounding the droplet are mostly fuel, since very little oxygen has had an opportunity to mix in. Thus, the area is greatly above the UFL and cannot ignite or burn. As time goes on, more vapors are released from the droplet, but vapors also spread out. This motion is due to both diffusion and convection. Since this is a hot-surface ignition problem, the environment around the droplet is necessarily at a different (higher) temperature than the droplet. The nature of the convective motion will depend on the details of the test environment. In the simplest case, the droplet might be dropped into a spherical cavity where the walls are heated to

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[1] 'Induction period' is the term used in chemical literature to denote ignition time.

[2] The equivalence ratio, φ, is defined as $(\text{fuel/air ratio})_{\text{actual}}/(\text{fuel/air ratio})_{\text{stoichiometric}}$. Consequently, the mixture is lean for $\varphi < 1$, and it is rich for $\varphi > 1$.

a uniform temperatures. Then, the vapors will puddle along the bottom, since they will be colder and denser than the surrounding volume. A more complicated situation is if the droplet is dropped onto a heated plate, which is situated in a room of ambient temperature. Prior to the droplet being discharged, a convective plume will be established above the heated plate, due to the temperature differences. When a droplet lands in such an environment, its vapors will get swept upwards, due to the prevailing upward velocity.[3] At the same, since the vapors have been released in a gas which is air, the concentration will progressively drop due to mixing.

Whether the released droplet will ignite or not, depends on a number of factors. Ignition can only take place if a volume exists where the fuel concentration is between the UFL and the LFL, and the temperature is at or above the AIT. Furthermore, a small volume of the fuel/air mixture must remain within the flammable range and above the AIT for a time equal to or greater than the required residence time. Otherwise, the vapors will just flow out of the environment without ignition. Even though the problem can be described in a phenomenological manner, the answer to this problem cannot be obtained by means of any simple calculation. Instead, either testing or numerical computation modeling is needed.

Despite the early start, however, experimental research on the HSIT problem has neither been copious nor systematic. Much of research has been motivated by problems of the armed forces, specifically ignitions in the engine nacelles of military aircraft. This is a very important problem, but it can require some extrapolation to apply such findings to other contexts. The first systematic review of the whole topic—not narrowed to aircraft environments—was undertaken by the present author in the *Ignition Handbook* [5].

The focus of the present article is to provide practical advice and, specifically, to delineate what tests will be appropriate for what environments, and which ones will not. It should be emphasized that the determination of the hot surface ignition temperature (HSIT[4]) is generally undertaken experimentally, not from theory or use of computational models. The analogy with AIT determination is relevant to consider here. Various theories and numerical models have been published which endeavor to compute a value of the AIT for a certain fuel/oxidizer mixture, at certain conditions. But obtaining the needed input data, especially data for a sufficiently good chemical kinetics model, is a task which is cumbersome and difficult. By contrast, running an AIT test is simple and economical and, if the test is conducted according to an accepted standard, the expectation is reasonable that what is obtained will be reproducible data, i.e., results which will be quite similar if repeated in a different laboratory. But, it will be shown later, that standardized HSIT tests are not available which are reasonably conservative and applicable to

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[3] Note that, in some cases, a discharged droplet will not reach the hot surface, since it will fully vaporize enroute. Whether this happens will depend on the size of the droplet, the discharge height, and the temperature and velocity details of the plume.

[4] Some authors use the term MHSIT, denoting ‘minimum hot surface ignition temperature.’ This is not correct usage, since the minimum HSIT is the AIT, and a distinction should be maintained between HSIT and AIT.

a broad range of problems. Thus, the experimental problem becomes somewhat more difficult, in that guidance must be taken from appropriate research papers.

2. Theoretical Treatments

A number of authors have endeavored to provide a theoretical treatment of the hot-surface ignition problem, and details are available in [5]. All of these focus exclusively on ignition of atmospheres containing a uniform concentration of a fuel gas. This allows a viable theoretical treatment, but is not helpful towards most practical problems, which typically involve a leak of a vaporizing liquid. In such cases, the fuel concentration cannot be even approximately uniform, and there is likely to be a strong two-phase effect, that is, the fuel in both its liquid and its vapor state. For a uniform fuel concentration, Semenov's theory is invoked [5]; however, the theory is too simplistic for practical problems, due to assuming a uniform temperature within the volume and a fixed convective coefficient as the heat loss boundary condition. A theory providing a more realistic treatment of heat losses was proposed by Laurendeau [6], however comparisons against experimental data indicated that major ad hoc modifications were needed to correlate data successfully [7].

Liquid aerosols, sprays, and other practical problems involving a liquid phase are innately greatly more complex than a hot body in a gaseous atmosphere of uniform concentration. Thus, no simple theory should be envisioned as being viable, but numerical modeling may be feasible. Vaivads et al. [8] made an early effort at modeling using a commercial CFD code, FLUENT. As shown below, experimental findings are that lower flash-point liquids require a high temperature for hot-surface ignition to occur. Unfortunately, Vaivads et al. obtained modeling results showing the opposite trend. Li et al. [9] subsequently concluded that this failure occurred since Vaivads et al. attempted to create a 2-d model of a geometry which must be modeled in its true, 3-d extent. Li et al. themselves then set up a 3-d model using the NIST FDS code. They concluded that such a model is able to adequately represent certain experimental features of hot-surface ignition. However, their study did not lead to identification of any data trends or development of engineering formulas. Later, Boussouf et al. [10] presented another FDS-based study of the hot-surface ignition problem. Most recently, Pedersen et al. [11] used ANSYS CFX in the first known effort where the authors were able to correctly establish some trends for the variables governing the HSIT using a CFD code.

3. The Probabilistic Nature of Ignition

Before delving into the experimental aspects of hot-surface ignition and the hot-surface ignition temperature (HSIT), it is useful to consider that the ignition temperature is properly considered to be a probabilistic variable. This means that, at low temperatures, the probability will be 0% that ignition will occur. And for high temperatures, the probability will be 100% of ignition occurring. But these two regimes will be separated by a temperature regime where the probability is

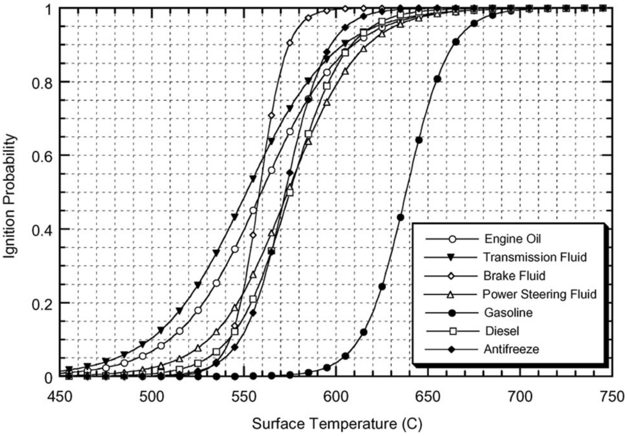

Figure 2. HSIT values, displayed as cumulative probability distribution curves, for a number of automotive fluids studied by Colwell and Reza [12] (Copyright © Springer).

something in between 0% and 100%.[5] This is true for any form of ignition, but until recent years, the published literature did not adequately recognize this. When the present author published the *Ignition Handbook* [5] in 2003, it required a concerted effort to locate even one example of high-quality data presented as a probabilistic graph.

In the intervening years, the work of Colwell [12, 13] is especially notable, due to the research on HSIT that he published where all the data were presented as probability graphs (Fig. 2). Other authors [e.g., [14–16]] now follow the lead of this work, although this does not make the task of the engineer easier. Instead, decision-making becomes more complex. If an HSIT for a certain fuel (under test conditions similar to the end-use environment) is X, and the temperatures in actuality are $> X$, then the decision is simple: conditions are unsafe. But what if the actual temperature is Y, and the probability of ignition at $Y = 7\%$? Is that safe enough, or not? The profession does not currently offer any easy guidance.

It may be noted that Colwell et al. did not assume any particular probability distribution function and simply plotted their results on linear x- and y-axes. It would be useful for future researchers to investigate whether a normal probability distribution function, or some other function best represents the data, and then present plots on axes which lead to a straight-line data presentation.

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[5] For most fuels, the cumulative probability distribution is a monotonically increasing function of the temperature. But for fuels, under some conditions, anomalies have been found experimentally, and unusual probability distribution functions may be encountered.

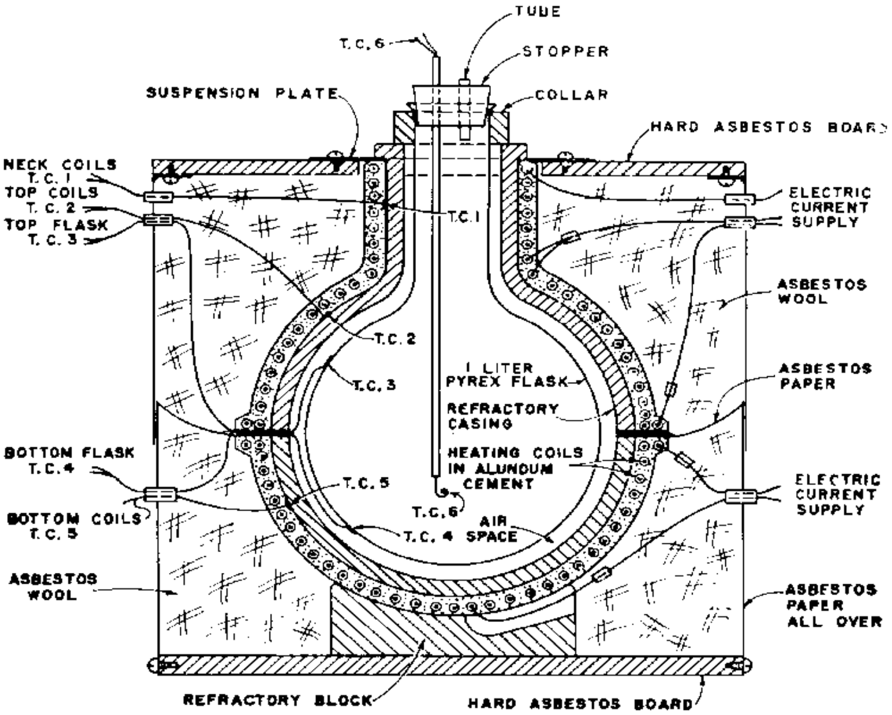

Figure 3. The Setchkin flask apparatus for AIT of liquids [17].

4. Measurement of AIT

Before considering details of hot surface ignition, it is important to understand how measurements of the autoignition (AIT) temperature of liquids, gases, or vapors are made. First, it must be understood that, with the exception of a few very unusual substances, liquids themselves do not ignite. Instead, when a liquid is involved in an ignition, it is actually the vapor from the liquid that plays the role of the fuel in the combustion process. Thus, perhaps it is not too surprising to realize that the most common type of AIT test involves an apparatus into which the test substance is introduced in liquid droplet form. Figure 3 shows the Setchkin flask test for the AIT. This apparatus was developed in 1952 [17], but the present-day test, ASTM E659 [18], uses a configuration which differs only in minor details. In an AIT test, the flask is electrically heated and assumes an essentially uniform temperature inside it. The specimen is introduced into the cavity by a dropper, and drops of reasonably volatile fuels tend to volatilize before the drop would hit the cavity wall. Since the neck forms only a tiny fraction of the periphery of the cavity, *the fuel/air mixture inside the cavity is essentially fully enclosed by a uniform temperature hot surface*. When handbooks tabulate AIT values, the data are most commonly obtained from ASTM E659 or from a test method which is functionally very similar.

5. The Nature of the Hot Surface Ignition Environment and its 'Enclosedness'

In the autoignition test, the environment is very simple: the fuel is dropped into a uniformly heated cavity, and the specimen is thus surrounded by the same temperature from all directions. Buoyancy is minimal, since there are no appreciable temperature differences, apart from the temperature of the fuel aliquot deposited. And, the specimen has nowhere to go—there is no exit channel. Meanwhile, the hot-surface ignition environment is notably different. For ignition to occur, a location *in the gas* has to exist where

(a) The temperature is at or above the AIT;
(b) The fuel concentration is between the LFL and the UFL, as determined for that particular temperature; and
(c) The fuel/air mixture stays in the high temperature zone for a sufficient time.

Such a location will not exist unit the hot surface is sufficiently hotter than the AIT. From these considerations, it can also be seen that if the hot surface forms a larger fraction of the environment, the temperature needed for ignition will drop, since there will be less of a dropping temperature gradient away from the heated surface.

In a state-of-the-art assessment of the ignition field, Babrauskas [19] noted that hot-surface ignition is one of the areas where published results show some extreme variations in the data. It is suggested here that these variations are not all due to random chance, nor due to poor technique. Instead, the geometric environment and its 'enclosedness' is seen to be a crucial variable.

It was noted above that the AIT is measured in an environment where the specimen is surrounded by a flask, the walls of which are heated to a uniform temperature. If this is the environment, then the measured ignition temperature will necessarily be the AIT. From this, it can now be noted that the HSIT involves exposure conditions where the specimen is **not** fully surrounded by an enclosure of uniform temperature. If the hot surface, when viewed from the specimen location, forms an infinitesimally small subtended angle, then no ignition will occur. But if the subtended angle is significant, and the temperature of the hot surface is sufficiently hot, then ignition may occur. In real-life accidents, the hot surface may be the exterior of an exhaust manifold, a catalytic converter, a lamp, etc. These objects are likely to have exceedingly non-uniform surface temperatures (and possibly an exceedingly non-uniform shape also). Thus, the general case can only be addressed by tailor-made ad hoc experiments.

But it is useful to consider some thought experiments, in order to facilitate the understanding of the problem. Consider a hot surface which is of uniform temperature. From the point of view of the radiant heat flux impinging on the sample of fuel, it may also be seen that decreasing the hot surface temperature, but increasing the angle it subtends may lead to an unchanged probability of ignition. This suggests that the angle subtended by the hot surface is one of the critical problem variables.

In the simplest case, it would be possible to define a nondimensional variable η, where η = fraction of the area of the surrounding sphere that is subtended by the hot surface. In other words, since an entire sphere comprises 4π steradians, η = (solid angle subtended by the heated surface)/4π. In such a case, it would be possible to present a graph of HSIT, versus η. The temperatures on the graph would start at some high value as $\eta \rightarrow 0$, and then HSIT $\rightarrow$ AIT as $\eta \rightarrow 1$. Most practical problems are too complex to be amenable to this kind of treatment, nonetheless the analysis should be helpful for establishing a qualitative understanding.

In practice, the geometry will rarely be simple enough to be quantified by a solid angle from a hot surface which is of uniform temperature. Instead, it may useful to adopt the qualitative term ‘enclosedness.’ An actual hot object, such as an engine exhaust manifold, is likely to be both convoluted and highly non-uniform in temperature. It may also contain areas which are closer to ambient temperature than they are to the peak hot-surface temperature. This suggests that enclosedness can play two roles. In general, segments of the enclosing boundary can be of three types:

(1) no surface; that is, open air;
(2) an unheated surface; or
(3) a heated surface.

To achieve ignition, it is necessary to capture a small volume of the fuel/air mixture and to heat it up sufficiently. An unheated surface will not assist in heating the specimen, but it will help in restraining it from readily departing the heated area. Thus, while increasing the subtended angle of the heated surface will be most favorable towards promoting ignition, replacing a certain portion of open-air periphery with an unheated surface can also assist in achieving ignition, although less effectively. The concept of enclosedness is sufficiently broad to encompass both heated and unheated surfaces.

6. Ignition of Gases or Vapors

We first consider, in this section, the hot surface ignition of gases or vapors where a liquid phase is not involved. Thus, permanent gases are considered, along with vapors of liquids where the vaporization has been accomplished remote from the area of interest. Thus, environments are considered here where the fuel/air mixture is uniform and fuel concentrations do not change with location.

Many studies on hot-surface ignition have identified the major role of the area of the hot surface. Figure 4 shows the data from Müller [20] and Cutler and Brearley [21]. Two traits are readily apparent: (a) increasing the area of the hot surface leads to a lower observed HSIT; and (b) a straight-line plot is obtained if the data is plotted on semi-log axes.

The laboratories of the former US Bureau of Mines (BoM) conducted the most extensive research on this subject. Kuchta [22] compiled the BoM data and simi-

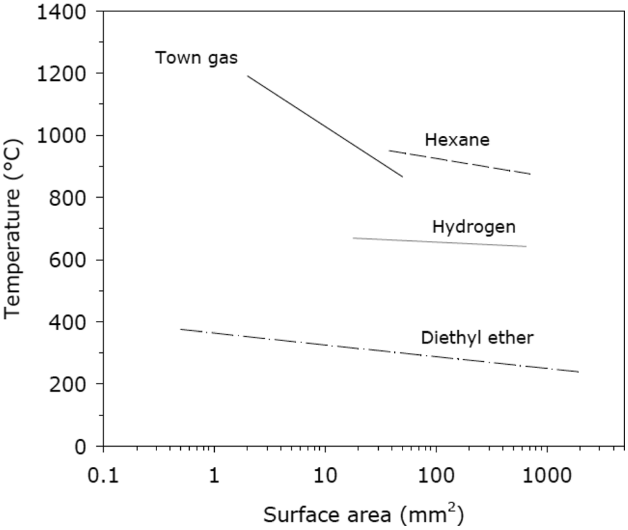

Figure 4. Effect of hot surface area on ignition of several gases or vapors ([5]; data from Müller; Cutler and Brearley).

larly found a straight-line relationship for a number of vapors (Fig. 5), when plotted on a semi-log scale. The functional relationship represented by all of the straight lines is:

$$T_{ig} = a - b \ln A$$

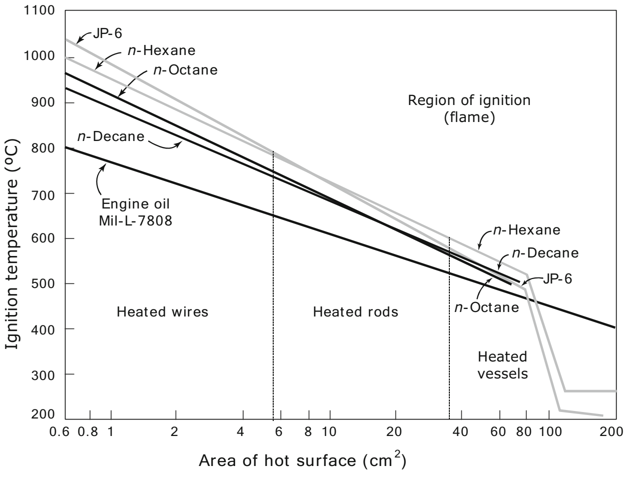

Figure 5. Ignition of vapors from hot surfaces: the effect of surface area ([5]; data from Kuchta).

where A = surface area (cm^2) and a and b are different constants for each fuel. But there are some exceptions to a single straight line representing all the data. JP-6 and *n*-hexane exhibit kinked curves, with a strong discontinuity at ca. 90 cm^2. This is due to the fact that, under the test conditions, the latter two fuels exhibit a cool-flame ignition [5] when tested in a large enough vessel. Engine oil does not show a cool-flame ignition, while the other fuels were not tested with large enough heated areas to assess their trends. Note that the area of the hot surface is a quantitative measure which is related to the enclosedness of the environment, even though it is not nondimensional.

Another study where the effect of enclosedness was recognized was that of de Lemos Duarte [23]. She made a study of the HSIT of propane, using a Nichrome strip as a heat source. By varying between an unenclosed geometry and inert walls 40 mm high on both sides of the heating strip, she was able to document about an 80C drop in the recorded HSIT.

7. Ignition of Drops, Sprays, Streams, and Aerosols

The other configuration for hot-surface ignition that must be considered is one which involves vaporizing liquids. A liquid is initially discharged in some manner into the environment, and this can be in the form of discrete drops, or else sprays, streams, or aerosols. The characteristic shared by all these situations is that initially there is no fuel in the vapor phase, but then it progressively increases as the process continues. The evaporation, and subsequent ignition, of a single droplet placed on a hot surface has been studied by several authors, who have identified as many as 6 different fluid-mechanical regimes for the subsequent behavior. A number of relationships can be established from such studies [5], but these are generally not of direct relevance to fire safety problems, since the ignition of a single droplet would hardly ever be a cause for safety concern. Thus, at this point, attention will be turned to sprays, streams or aerosols.

Since the most common scenario may involve a hot engine manifold, it is appropriate to devote some specific attention to this particular hot surface. It is also useful to know that exhaust manifold temperatures in passenger cars can vary over a large range, and one study reports a range 200°C–600°C [24]. It is often considered that a dull-red-hot temperature of 600°C (or higher) will only be reached if there is a serious engine problem. One author recommends that if the vehicle that is not malfunctioning, the upper limit is 500°C [25]. This does not appear to be reliable, since, in some unpublished tests, the present author measured over 620°C on the manifold of an off-road motorcycle which was in good working order, but was merely revved to high RPMs on a hot summer day. But even 300°C is above the AIT of many common liquids, thus researchers have needed to explain why such ignition incidents are relatively rare.

The simplest arrangement is individual droplets being dropped at low speed onto the surface. Yet, even this situation is highly complex, since the heat transfer and fluid mechanics details of a drop in contact with a hot surface are intricate. Experiments indicate that a fuel released onto a hot surface as single drops may

Table 1
Hotplate Ignition Temperatures for Single Drops of Various Fuels [12]

	Ignition temperature (°C)			
Fuel	$P = 1\%$	$P = 10\%$	$P = 50\%$	$P = 90\%$
Antifreeze	519	521	573	598
Aviation gas	601	636	667	700
Brake fluid	525	542	559	575
Diesel fuel	505	542	575	645
Engine oil	455	510	560	612
Gasoline	585	612	638	664
Jet A	519	552	583	614
JP-8	517	549	577	606
MIL-H-5606	532	570	606	641
MIL-H-7808	555	656	596	617
MIL-H-83282	525	549	570	592
Power steering fluid	483	531	574	617

show sustained ignition only within a narrow range of temperatures, and raising the temperature higher produces only flashing [5]. Colwell and Reza [12] obtained systematic data for single-drop ignition for a variety of fuels. This study is especially interesting since it was reported on a probabilistic basis (Table 1). A similar probabilistic study, using a similar test rig (highly open) was later reported by Shaw et al. [15], giving data for diesel and various types of biodiesel fuels. Despite a protocol which was quite similar to that of Colwell and Reza, the results of Shaw et al. were notably different. For example, Colwell and Reza found an HSIT of 575°C for diesel fuel, at the $P = 50\%$ level, while Shaw et al. found 475°C–480°C, a value nearly 100°C lower. Similarly, for gasoline, Colwell and Reza reported 638°C, while Shaw et al. found 585°C, some 53°C lower. Additional data are available for pure chemical compounds [5], but pure chemical compounds are less commonly involved in accidents.

Table 2
Early Research on Hot Surface Ignitions Summarized by Scull

Substance	HSIT (°C)
Gasoline	560; 718–760
Aviation gasoline	454; 585
Ethanol	690
Kerosene	650
Diesel fuel	718–760
Motor oil	718–760
Hydraulic fluid	400
Llubricating oil	430

Table 3
Hot-Surface Ignition Temperatures Determined by Goss

Substance	HSIT (°C)
Brake fluid (AP brand, DOT 3)	400
Brake fluid (Unipart, DOT 3)	400
Brake fluid (Castrol Girling Crimson)	650
Motor oil	600
Silicone oil	600

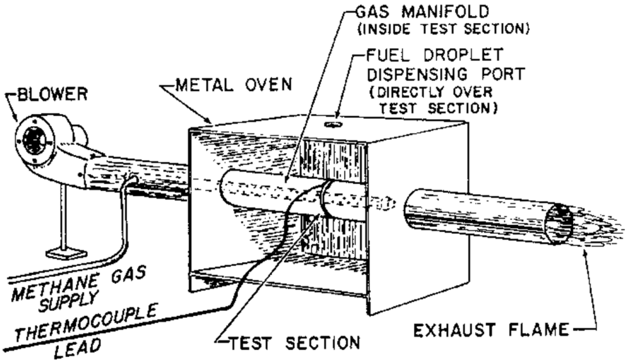

Figure 6. Hot manifold simulation rig used by Severy et al. [28].

Table 4
HSIT Values Obtained by Severy et al., Along with AIT Values from Refs. [5,71–73]

	HSIT		AIT	(HSIT–AIT)
Fluid	Marginal ignition (°C)	Consistent ignition (°C)	(°C)	(°C)
Brake fluid	ca. 410	ca. 500	329	171
Diesel fuel	521	549	256	293
Gasoline, leaded	ca. 510	610	250	360
Gasoline, unleaded	ca. 520	627	313	314
Motor oil	ca. 320	ca. 420	232	188
Propane (liquid)	ca. 675	ca. 775	500	275

In general, however, the bulk of both the practical concern and the published experimental studies have focused on sustained discharges rather than individual drops, since the hazard with these can be expected to be greater (see below).

For a variety of substances that might potentially ignite on engine manifolds, Scull [26] published in 1951 summaries of findings from early literature (Table 2). These results are still useful today to establish the experimental range for some

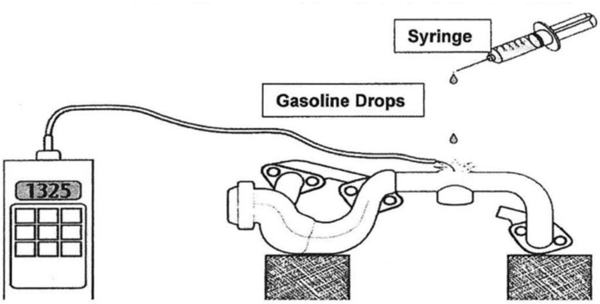

Figure 7. An open, unenclosed test arrangement adopted by LaPointe et al. [29].

common substance. Goss [27] examined the ignition of several fluids on a hot steel manifold and provided data on these (Table 3). This work is obviously limited in that the author only undertook to vary temperatures in 50 °C increments.

The most useful compilation of practical data may be that presented by Severy et al. [28], who constructed a manifold simulation rig which was enclosed on five sides and open on the front (Fig. 6). Using ten drops of liquid and no forced air flow, they defined two levels of ignition—'consistent' and 'marginal.' Their results are given in Table 4. A number of their values are identified here as approximate, since the authors only gave those results in a poorly drawn figure. The partial enclosure in Severy's rig can be considered to be a realistic, albeit simplified representation of conditions inside an engine compartment.

An opposite tack was taken by investigators at Ford Motor Co. [29], who conducted tests on ignition manifolds completely in the open. In addition, they selected a straight-run section of pipe (Fig. 7), even though ignition would be much more likely to occur in portions of the piping that are reentrant or recessed. Under those conditions, it is not surprising that some very high temperatures were required for gasoline to get ignited: 794°C–826°C for iron piping and 718°C–733°C for stainless steel.

An interesting set of experiments was reported by Haussmann and Matta [30], who noted that, in some small-size gasoline engines, hot-surface ignitions sometimes occur *inside* the exhaust system, after the engine has been shut off. Heated air flows can continue afterwards due to temperature differences, and this flow can entrain fuel vapors from the carburetor. Unfortunately, they did not use gasoline in their actual experiments, but rather hexane.

Myronuk [31] initially conducted flat-plate experiments, but discovered that the residence-time was a critical factor. In his flat plate geometry tests, the mixture did not stay in the hot zone long enough for ignition to occur. Thus, he then mocked up the fin-like obstructions that can be found on a real engine surface. He considered that this more realistic test geometry both prolonged the residence time and helped to create a stagnation mixing region. His test results showed that there was no significant difference between the ignition of JP-4 and JP-5 aviation fuels and MIL-H-5606 hydraulic oil, thus the results are shown in Fig. 8 as one

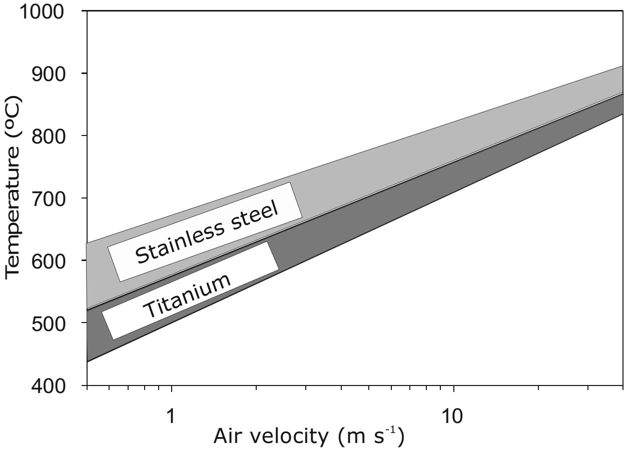

Figure 8. Myronuk's results for ignition of JP-4, JP-5 and MIL-H-5606 hydraulic fluids on hot engine surfaces [5].

Table 5
Effect of Various Variables on the HSIT, as Assessed by Bennett

Variable	Effect on HSIT, predicted	Effect on HSIT, observed
Surface roughness	Decrease (?)	Decrease
Air temperature	Decrease	Decrease
Air pressure	Decrease	Decrease
Air velocity	Increase	Increase
Fuel volatility	Increase	Increase
Fuel boiling point	Decrease	
Fuel specific heat	Decrease	
Fuel heat of vaporization	Increase (?)	
Surface tension	Increase (?)	
Saturated vapor pressure	Decrease	
Fuel thermal conductivity	Decrease	

band. On the other hand, he found that the type of metal used made some difference, also shown in Fig. 8.

8. Effects of Variables

In 1998, Bennett [32] published a literature review on hot surface ignitions of liquids/droplets/sprays, focusing on studies of military interest. Of notable interest is his assessment of the effects of various variables on the ignition temperature, and this is shown in Table 5; the question marks ("?") denote an uncertain determination, according to Bennett. The "predicted" values refer to some semi-quantitative scaling relationships which Bennett utilized. Note that Bennett did not study what the present author has determined to be the most important problem variable, the degree of enclosedness. Bennett also studied the effects on ignition time. These are not tabulated below, since generally the safety problem consists of avoiding ignition, rather than delaying it. It may further be noted that ignitions, when they do occur, are generally very rapid (several seconds, or less), further noting the lack of significant benefit from ignition delay.

8.1. Degree of Enclosedness

The degree of enclosedness has already been presented earlier in this paper. Thus, only some highlights will be given here. The AIT of *n*-hexane is 223°C [5]. When studying an environment in the interior of a heated tube, a geometry with a substantial degree of enclosedness, Haussmann and Matta [30] found an HSIT of 550°C. Meanwhile, in an open-air arrangement where only a metal strip was heated, Demetri and White [33] found an HSIT of 950°C–1000°C. Even though the environment of Haussmann and Matta was substantially enclosed, only a small portion of it was at the maximum temperature; this is the reason why their HSIT value was still greatly above the AIT. Additional data of Henningsson [34], discussed below, are also included. He used a test rig with a large heated surface, surmounted by a large unheated shroud. All the above results are summarized in Table 6.

When the bounding surfaces are all isothermal, the degree of enclosedness is directly related to the total heated surface area. Figure 5 shows a summary of extensive studies conducted by the BoM. Note the scale in this graph. The perimeter surface area of a 4-inch cube is 600 cm^2, which is greater than the maximum x-value on the graph. Similarly, the inside area of the flask in the ASTM E659 [18] test for AIT is approximately 300 cm^2, which is also beyond the largest value plotted.

Table 6
Effect of the Degree of Enclosedness on the Ignition Temperature of *n*-Hexane

Test condition	Ignition temp. (°C)	(HSIT–AIT) (°C)
AIT	223	0
HSIT recommendation of API	423	200
Large heated surface, with high degree of enclosure (unheated)	480–500	257–277
High degree of enclosure, but not all at a high temperature	550	327
Hot strip in open air	950–1000	727–777

8.2. Air Velocity and Residence Times

Increasing the air velocity[6] increases the minimum temperature needed to achieve a hot-surface ignition, for example, see the results obtained by Myronuk [31] in Fig. 8. Atkinson and Eklund [35] obtained similar results. At sufficiently large velocities, fuel drops which could otherwise reach a hot surface may simply be entirely blown off [36], leading to very high values of HSIT, or no ignition at all. The conclusion with regards to testing is that specimens should be tested at quiescent conditions, in order to obtain the conservative results, unless it is known that the potential ignition area will never be free of a wind velocity. Pedersen et al. [11] were successfully able to simulate trends similar to those shown in Fig. 8 using a CFD modeling code.

The results in Fig. 8 show that the HSIT increases with increasing air velocity all the way from the lowest value plotted, 0.5 m s^{-1}. But different results were found by Imamura et al. [37] who studied hot-rod ignition of propane. Over the flow range of 1.0 m s^{-1}–4.0 m s^{-1}, the HSIT was found to be constant. This may be since Imamura et al. studied a uniform fuel gas/air mixture, while Myronuk discharged liquid fuels onto a hot manifold. At higher air flow rates, the HSIT of pentane/air mixtures does increase with increasing velocity; Mullen et al. [38] showed this over the range of 46 m s^{-1}–104 m s^{-1}.

Closely related to air velocity is residence time. As noted above, ignition will not be possible if residence time is too low. Very few studies exist examining the role of residence time in hot-surface ignition experiments. From more traditional combustion experiments, it can be concluded that required residence are usually not more than 1 s, and may be much less [39, 40].

8.3. Air Temperature

The data on the effect of ambient air temperature are inconsistent. Strasser et al. [41] examined the effect of raising the ambient air temperature on MIL-H-83282 hydraulic fluid. At stagnant-air conditions, no effect was found when increasing the ambient air temperature from 27°C to 177°C. But if the temperature was raised and a non-zero wind velocity was also imposed, then higher ambient air temperatures did lead to lower HSIT values, although the effect appeared to be hardly greater than the experimental data scatter. Mullen [42], on the other hand, studying pentane in air, also found minimal effects at low imposed wind velocities, but a major effect for velocities > 40 m s^{-1}; note, however, that these are very large velocities and would typically be found only in jet engine nacelles or in vehicles moving at highway speeds. The effect of ambient air temperature on HSIT was also examined by Pedersen et al. [11] using a CFD modeling code. They also found decreases in the HSIT with increasing air temperature, but they only studied very elevated (100°C–500°C) values for ambient air temperature.

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[6] In case of environments which involve a uniform fuel/air mixture, the velocity is to be understood to be the velocity of this mixture.

8.4. Air Pressure

Johnson et al. [43] documented that lowering the air pressure results in a raising of the HSIT for JP-4, JP-8, and MIL-H-5606 hydraulic fluid. Rehman [44] presented recent data for diesel fuel, while McTaggart [39] for natural gas, and Menon et al. [40] for hexane. For all these experiments, the results tend to show a straight line with a downward slope, when plotted on a semi-log graph, with the pressure on the (log) x-axis and the HSIT on the (linear) y-axis. The data of all these studies can be represented by the equation:

$$\frac{HSIT}{HSIT_{\mathrm{r}}} = \left(\frac{p}{p_r}\right)^b$$

where r denotes reference conditions, typically at $p = 1$ atm, and $b \approx -0.1$. Such data are especially relevant to jet engine safety, concerning ignitions in flight. Note that the hazard increases (lower HSIT values) for $p > 1$ atm, and decreases (higher HSIT values) for $p < 1$ atm. Thus, conditions become less hazardous at high-altitude flight conditions.

8.5. Turbulence Intensity

No experimental studies are known where the turbulence intensity effects would have been quantified. But Pedersen et al. [11] made some predictions using a CFD modeling code. For turbulence intensity of ≤ 5%, they found no effect. But

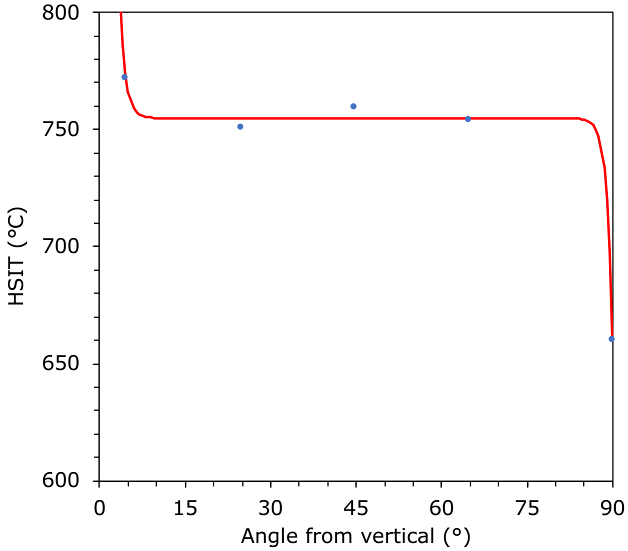

Figure 9. Effect of inclination of hot surface on the ignition of ethane, where 0° denotes wall orientation, and 90° denotes ceiling [45].

increasing the intensity from 5% to 10% led to a slight (30°C) increase in the HSIT.

8.6. Hot Surface Orientation

The effect of hot surface orientation ought to be directly related to convective effects. Johnson et al. [43] found that ignition was more difficult from a vertically-oriented hot surface, as opposed to horizontally. They attributed this to the fact that the vertical orientation provides greater convective cooling than the horizontal. A more detailed study was done by Hamins and Borthwick [45], where they examined the HSIT of ethane as a function of the angle of inclination of the hot surface from the vertical. Figure 9 shows that, over a wide range of angles, there is no significant effect. But as the angle approaches 0º or 90º, a significant effect will be found. Their results confirmed the basic findings of Johnson et al.—a horizontal orientation provides a lower HSIT than a vertical orientation. Furthermore, it can be noted that the horizontal orientation can be of two types—floor or ceiling. Laurendeau [6] provided data showing that the HSIT values are ranked, low to high, as: $\mathrm{HSIT_{floor}} < \mathrm{HSIT_{ceiling}} < \mathrm{HSIT_{wall}}$.

8.7. Hot Surface Material Type

There is extensive evidence that the type of material from which the hot surface is made does influence the HSIT. Most of the research on this topic was done for, or by, the US Air Force, thus the information available is generally limited to materials—almost all being metals—of interest to the Air Force. Figure 10 shows results obtained by Myronuk [31]. Note that at zero imposed air velocity, the values of HSIT span a range of 115°C.

Catalytic surfaces (e.g., platinum, palladium) can show some effects very different from those for other material types. Noting, however, that such surfaces are almost never associated with accidental ignitions, details of the research can be found in Ref. [5].

8.8. Hot Surface Roughness

Surface roughness of the hot surface plays a role in the evaporation process which is complicated and only partly understood. Bennett [46] reported on some preliminary research indicating that a surface with micro-cavities may be less prone to igniting some liquids. On the other hand, Gerstein and Mansour [47] found lower HSIT values for rough surfaces, compared to smooth ones. Finally, Mullen et al. [38] found no difference between smooth and rough stainless steel surfaces.

8.9. Fuel Quantity, or Fuel Release Rate

For small amounts of fuel released, Knowles [48] showed that larger quantities of fuel released result in lower hot surface temperatures being needed for ignition (Table 7).

For experiments where a small stream of MIL-H-5606 hydraulic fuel was directed at a hot manifold, Parts [49] obtained the data shown in Table 8. For high

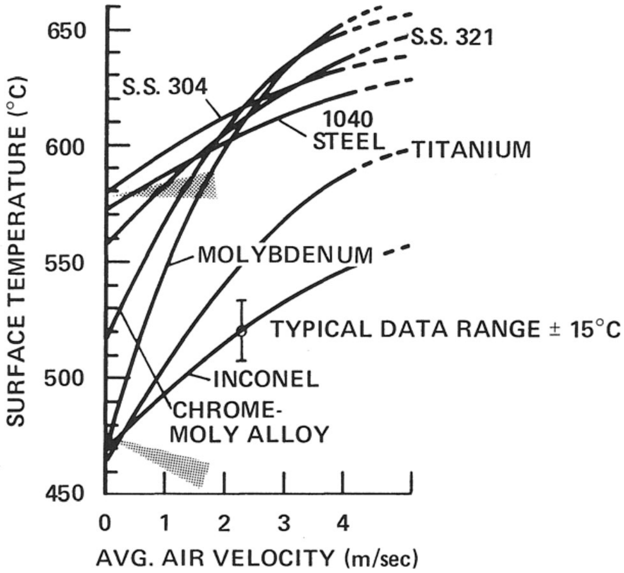

Figure 10. Effect of hot-surface material on the HSIT of JP-4, as reported by Myronuk [31].

(> 1.7 mL s^{-1}) flow rates, the HSIT was greatly below that needed at a lower flow rate (0.35 mL s^{-1}). But the intermediate range showed an unusual trait: Ignitions were found for temperatures between 388°C and 566°C, or else 704°C and above, with no ignitions over the range of 567°C–703°C. The author considered that this trait was due to the wetting behavior of the hydraulic fuel flowing over the manifold. In the lower temperature regime, the manifold surface was extensively wetted, but in the intermediate temperature regime, vaporization was sufficient to eliminate this direct wetting. However, conflicting findings were reported by Johnson et al. [43]. These investigators also sprayed MIL-H-5606 on heated manifolds at rates ranging from 1.0 mL s^{-1} to 12 mL s^{-1}, yet saw no significant effect of flow rate on the HSIT. The conclusion that might be drawn from these conflicting findings is that differences in the details of the manifold assemblies used overwhelmed the fuel delivery rate variable.

Table 7
HSIT of Spills of Turbine Oil on a Hot Surface [48]

Quantity	Min. ignition temp. (°C)
2 drops	450
5 mL	380
30–60 mL	315

Table 8
HSIT for Hydraulic Fluid Streamed Upon a Hot Manifold [49]

Flow rate (mL/s)	Min. ignition temp. (°C)
0.35	804
1.0–1.7	388–566; 704 +
> 1.7	482

For large amounts of fuel released, there is an optimum fuel flow rate, which is typically related to the stoichiometry achieved at the hottest zone. Strasser et al. [41] demonstrated this for JP-4 and JP-8. The minima they found, however, were fairly shallow, with large flow rate changes leading to HSIT values rising by only 50°C–70°C.

8.10. Fuel Droplet Size

For fuels delivered as liquid droplets, the droplet size plays a role. Henningsson [34] determined that larger droplet sizes lead to a lower HSIT (Fig. 11). This can be an important question, and additional studies would be useful.

8.11. Fuel: Equivalence Ratio

Another fuel variable which is important to consider is the equivalence ratio, which is the nondimensional expression of the fuel/air ratio.

For gases, Vanpée and Bruszak [4] studied a large number of fuels and found inconsistent results. Large changes were never seen, but as φ was increased, the HSIT would either increase gradually or show a peak, then decrease, but for some fuels, a shallow minimum was seen (Fig. 1).

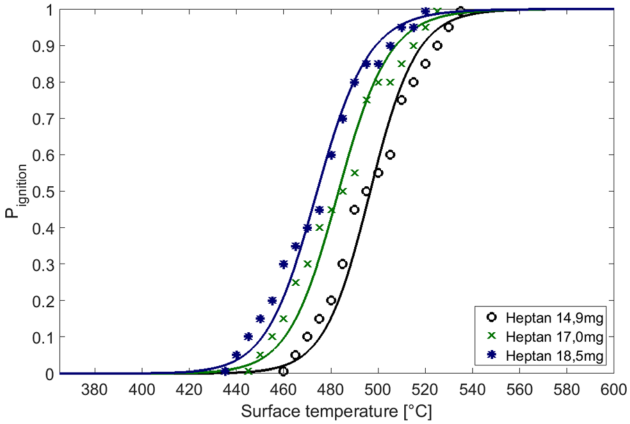

Figure 11. Effect of droplet size of heptane (as determined by weight of drop) on the HSIT, as determined by Henningsson [34].

For liquids, Menon et al. [40] presented some data for hexane, showing that HSIT is constant for $0.8 < \varphi < 3.0$. Meanwhile for $\varphi < 0.8$, the HSIT increased rapidly. On the other hand, Mével et al. [50] studied hydrogen and found a monotonically increasing value of HSIT all the way between the LFL and the UFL, although the total increase was only 160°C. Boeck et al. [51] studied hydrogen, hexane, and ethylene. They found that generally variations in HSIT were within the experimental data scatter over most of range of mixture fractions, except that values increased as the LFL or UFL were approached.

General guidance. The above results show that there is no general relationship for HSIT as a function of φ. However, in most cases, the changes of HSIT with the mixture fraction are small, and are likely to be within the data scatter. Thus, it can be reasonable to assume no effect of φ, except very close to the LFL or UFL.

8.12. Fuel Flash Point

Perhaps the most interesting finding concerning the HSIT is that there is an inverse relation (Fig. 12) between the flash point and the HSIT [5]. Substances having a lower flash point are more volatile, and it may not be intuitively obvious why more volatile fuels are harder to ignite at a hot surface than are the less volatile ones. To reach an understanding, it is essential to consider the details of the zone where ignition takes place. When a liquid fuel in the form of drops, sprays, etc. lands on a heated surface, the concentration of fuel at the surface is typically high and most likely the fuel will be above its UFL near the surface, meaning that ignition is impossible there. As one goes away from the heated surface, the fuel

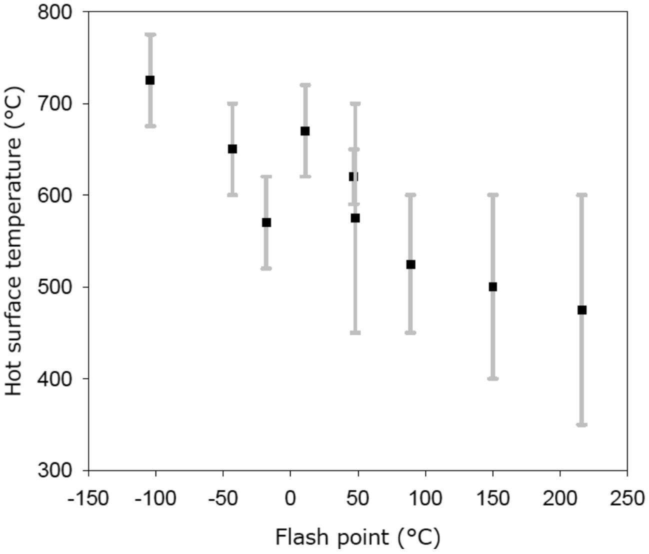

Figure 12. Relation between hot-surface ignition temperature and flash point (from Ref. [5]).

concentration will drop, but so will the temperature (on the assumption that the ambient environment is much cooler than the hot surface). If the fuel is very volatile, however, it will be required to go quite a large distance away from the surface before the concentration drops below the UFL and enters into the flammable region. But if this distance is large, then this location will be much cooler than the hot surface and ignition may not be possible there because the mixture is too cold. Consequently, the hot surface temperature will need to be increased further in order to make the distant location still hot enough. This is qualitatively the physical explanation for the relationship found in Fig. 12, although detailed modeling work (which should include the chemical nature of the fuel) has not yet been done to quantify this.

9. Safety Recommendations

Table 4 provides a list of recommended HSIT values (those presented by Severy et al.) along with the corresponding AIT values for the same fuels. The HSIT values average 267C above the corresponding AIT values, with the range for the difference being 171C–360C. Based on reasoning presumably similar to this, the American Petroleum Institute (API) issued a recommendation [52] that hot surfaces are likely to ignite fuels only if the surface temperature exceeds the AIT by at least 200°C in still air,[7] and by even a larger amount if an appreciable velocity exists. Engine designers typically use this recommendations in their work. The recommendation is obviously approximate, since it does not explicitly take into account the enclosedness of the environment, nor any of the other factors that might influence the hot surface ignition temperature. The recommendation should not be used when the hot surface largely envelopes the potential zone of fluid discharge, in which case the AIT should be used.

10. Standard Test Methods

There are few engineering test methods for HSIT that have been standardized, and none of them are appropriate for general-purpose usage, due to limitations of both their test rigs and their test protocols.

10.1. ASTM D8211, ASTM D6668, IEC 60,335–2-40, UL 60,335–2-40

The ASTM D8211 standard [53] was first issued quite recently, in 2018. This test is, effectively, a further development of the testing method earlier standardized in ASTM D6668, see below. The test method was developed solely for use in the industry sector dealing with refrigerant fluids, specifically for qualifying fluids into the ‘2L’ category [54]. A 5 g aliquot of a liquid specimen is sprayed from a spray nozzle onto a hotplate initially equilibrated to 800°C (Fig. 13). The specimen is observed for 2 min, and the only result reported is pass (no ignition) or fail (ignition). The hotplate itself is a stainless-steel disk, horizontally positioned. A cylin-

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[7] Note that the values obtained by Severy et al. were without an imposed wind velocity.

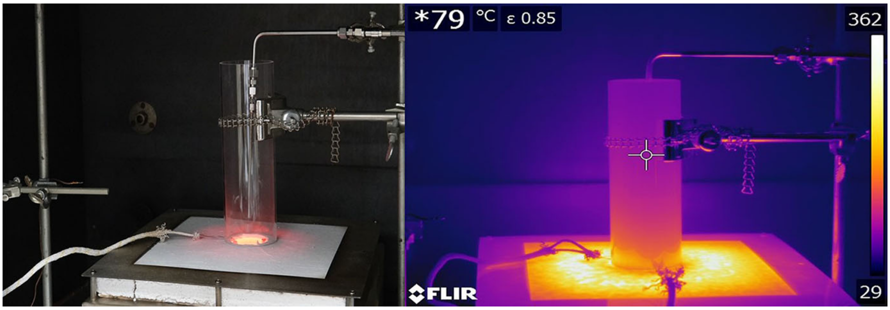

Figure 13. View of the ASTM D8211 test rig (Photo: Nina E. Gray, The Chemours Company).

drical quartz chimney is surmounted upon the rig, but spaced with a 4 mm gap. Thus, while the solid angle of heated surface viewed by the specimen is very small. However, a large view angle is provided by the ambient-temperature enclosure. Research with the standard has been described by several authors from the Chemours company [55, 56, 57].

The ASTM D8211 test has a long and convoluted history, all within the industry sector dealing with refrigerant fluids. It originated with ASTM D6668 [58], which was first issued in 2001. This method uses a similar apparatus, but of an earlier state of development. It is also a go/no-go test, but in this case heated to 815.5°C for 5 min. The test procedure is different from that in D8211 in that a graded series of droplets (0.1, 0.2, 0.5, and 1.0 mL) is to be used. Note that the 5 g quantity used in the D8211 test has a volume of around 6 mL, thus a much larger specimen quantity is used in the newer test. The use of a larger quantity of fuel in the D8211 version is not necessarily a conservative strategy, since the design of the equipment is such that a temperature drop on the order of 100°C occurs upon the initial deposit of a 5 g sample upon the heated disk [56].

In addition to the two ASTM standards, there are IEC and UL versions. The IEC version was introduced as Annex KK to IEC 60335-2-40 [59] in 2018. This is based on the ASTM D6668 version and uses 800°C as the criterion temperature. However, a single volume (1.0 mL) of test fluid is sprayed, and the observation time is 3 min, not 5 min. Another difference is that the method of discharging the sample is not specified in ASTM D6668, while specific specimen-feed features are standardized in detail in Annex KK. Annex KK of UL 60335–2-40 [60] is nearly identical, but replaces the 800°C hot surface temperature with 860°C.

10.2. ISO 20823

The older (2003) ISO test, ISO 20823 [61] is somewhat more versatile than ASTM D8211 in that the user is allowed to select a temperature of 700°C, or else an alternate temperature of choice. The design also makes a modest effort to simulate a hot engine-exhaust pipe. Unfortunately, the designers of the test did not understand the role of buoyancy of hot gases within the partial enclosure. In its broad features, the test resembles Severy's rig, but with a critical shortcoming. In Severy's rig, the most important feature is that there is a lid on top, allowing a certain amount of hot gases to accumulate underneath it. In the ISO 20823 rig, however, the enclosure is missing the top lid, allowing hot gases to freely escape (Fig. 14). The method is also limited in that, similar to the ASTM method, provisions are not made that the user determine the actual HSIT for the specimen fuel. Deleanu and coworkers [62, 63] published some data using this test method. The ISO method comprises a replacement for the withdrawn industry standard CETOP RP 65H [64].

10.3. FED STD 791 Method 6053

This Federal standard [65] features a very old test method (Fig. 15) which, however, is fairly similar[8] to the much newer ISO 20823. As presented, it is a go/no-go test for ignition at a HSIT of 704°C. The procedure is remarkably imprecise: drop "the test liquid at a rate of 10 mL in 40 s–60 s from various heights onto various points of the tube, and observe the ignition characteristics of the liquid." The protocol could presumably be improved, but the fact that there is no lid over the rig means that notably high (unconservative) values of HSIT will be reported. This can be contrasted to the rig of Severy, who realized that providing a lid is more important than providing a front wall, if reasonably conservative values of HSIT are to be reported. Limited research with this test method was reported by Snyder et al. [66].

11. Related Phenomena—Hot Surface Ignition of Solids

This paper does not cover the ignition of solid substances by hot surfaces, since the physics phenomena involved are different. However, since users may also encounter a need to obtain HSIT information for solids, some important literature references are provided here. The physics differs since solids are not mobile and will not rise upwards due to buoyancy (but in some cases they can pull away from a source of heat, due to shrinkage or melting). Same as for gases/vapors/liquids, no useful theory exists and the problem has to be approached from an experimental basis. A number of experimental findings and empirical trends are examined in Ref. [5]. One specialized area where hot-surface ignition of solids has been of major importance is in fire-resistance testing. The standard tests (ASTM E119 [67]; ISO 834 [68]) utilize an unexposed surface temperature criterion for certain classes of assemblies as one of several criteria for determining when failure occurs. Babrauskas has examined the research available on this topic [69]. Hot surface ignitions of solid objects may also occur due to electrical causes; these are discussed in Ref. [70].

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[8] Note that the Federal standard uses a 5-sided box, while the ISO standard a 4-sided one.

Figure 14. A droplet igniting on the hot manifold in the test rig of ISO 20823, from Deleanu et al. [62].

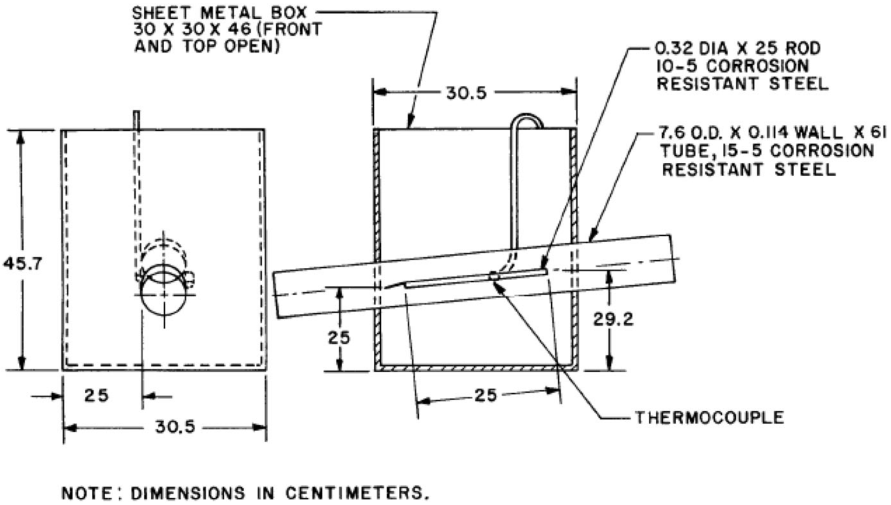

Figure 15. The test rig used in FED STD 791 Method 6053 [65].

12. Conclusions and Recommendations

Ignition from hot surfaces has been studied experimentally by numerous researchers, but there is not yet a theory or predictive equations that would allow the topic to be treated without having recourse to experiments or to published data.

Apart from the chemical nature of the fuel, the most significant variable governing the HSIT is the degree of enclosedness of the environment around the hot surface.

For ignition to occur due to the presence of a hot surface, the surface must generally be heated to a temperature significantly above the AIT. The reason for this has to do with the distribution of fuel vapors in the vicinity of the hot surface. A location *in the gas* has to exist where.

(a) The temperature is at or above the AIT;
(b) The fuel concentration is between the LFL and the UFL, as determined for that particular temperature; and
(c) The fuel/air mixture stays in the high temperature zone for a sufficient time.

Such a location will not exist until the surface is significantly hotter than the AIT (except for the case where the hot surface fully surrounds the combustible mixture).

Under any circumstances, assuming that HSIT = AIT will be a conservative assumption, since HSIT necessarily ≥ AIT. But this may be *too* conservative an assumption, since the API found that, under many common circumstances, HSIT $\approx$ AIT + 200°C. For low-consequence situations, simply using the API recommendation may be sufficient. But for high-consequence scenarios, efforts should be made to determine a more reliable HSIT value.

The available standard tests, ASTM D8211, ASTM D6668, IEC 60335-2-40, UL 60335-2-40, ISO 20823, and FED STD 791, were designed for some specialized industry needs and are not appropriate as means of obtaining general-purpose HSIT values. Especially, these would generally produce unconservative (too high) values of HSIT with regards to exhaust manifold environments. This is because such environments typically show a high degree of enclosedness by the heated surfaces, whereas the standard tests provide only minimal hot-surface enclosedness. The research of Colwell and Reza can provide valuable guidance for a statistical formulation of a testing program. Their test rig, however, provides the specimen with only negligible hot-surface enclosedness, and thus, for most vehicular applications, would not provide conservative results.

Given the lack of suitably general-purpose standardized tests, users have two recourses: (1) they can attempt to find a relevant HSIT value in the literature. If this approach is taken, assurance needs to be had that the real-life scenario does not present a higher degree of enclosedness than was present in the experimental study. Or, (2) they can conduct ad hoc tests, endeavoring to simulate adequately the environment in question. Here, two caveats are in order:

(a) The means of fuel delivery, the geometrical arrangement, and the heating regimen should adequately represent the end-use scenario. (The scenario adopted by Severy et al. will be conservative with regards to a majority of end-use scenarios. Thus, their data may be used in many circumstances.)
(b) The probabilistic nature of the ignition problem must be recognized. The user needs to determine the testing needed to be done to establish an ignition prob-

ability curve, along with a determination of the probability level at which results should be utilized.

In an automotive engine compartment, gasoline is typically the substance that is *least* likely to ignite from a hot surface, since it will be, by far, the most volatile substance to be found there. Nonetheless, gasoline can ignite on manifolds or other parts of internal combustion engines, if they attain temperatures over 520°C or thereabouts. However, when examining engine-compartment fires, investigators should also examine the possibility whether gasoline could have gotten ignited from defective high-voltage ignition wiring or appurtenant components.

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