

Spiking of Hydrocarbon Fuels with Silanes-based Combustion Enhancers

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The concept of spiking hydrocarbon fuels such as kerosenes with liquid silicon hydrides in order to render the fuel combination hypergolic and to improve the combustion efficiency is presented and preliminarily analyzed. In view of scarcity of available data, various approaches are used, among them quantum-mechanical *ab initio* calculations for the thermodynamics and shock-tube measurements for the kinetics of higher, liquid silanes. Based on these results and other data, performance predictions indicate that miscible hydrocarbon/silicon hydride fuels (HC/SH) have the potential to be stored in a single tank, to be hypergolic with many oxidizers, and to yield similar, partly better specific impulses (and volume-specific impulses) than hydrocarbon fuels without silane additives. A variety of hybrid HC/SH fuel combinations seems to be accessible, which might offer the possibility to design a fuel combination with characteristics adjustable in a wide range. The current and future availability of larger amounts of liquid silanes is discussed.

Key Words: Silicon Hydrides, Silanes, Chemical Propulsion

1. Introduction

The hydrides of chemical elements of the fourth main group of the periodic table are similar as concerns their chemical formulae and structure, but can also react fundamentally differently under certain aspects. In particular, the chemical reactivity increases dramatically as the atomic number increases. In other words, while generally, hydrocarbons are relatively inert, silicon hydrides (silanes) are much more reactive, and this trend increases even more with hydrides of germanium (germanes), the hydrides of tin (stannanes), and hydrides of lead (plumbane). This behavior is mirrored by the richness of compounds consisting of hydrogen and an element of the fourth main group. While the overwhelming diversity of stable hydrocarbon compounds is the basis of organic life, considerably fewer silicon hydrides are known. This trend is continued with germanes, and with tin, where only two stable stannanes are known, and with lead, where only the highly unstable plumbane is on records.

The root of these trends can be found in the ability of carbon, in contrast to the other group-IV members, to occupy sp -, sp^2 - as well as sp^3 -hybridized states. It has been stated already by silane pioneer Alfred Stock ¹⁾, that the electron affinities of C towards positive (H) and negative (O) elements are nearly the same and can be seen as the source of the diversity and richness of carbon compounds on this level. In contrast, for example, Si has a much stronger affinity towards O than towards H. In addition, the Si-Si bond is weaker than

the C-C bond. This is part of the reason why silanes are much more willing to decompose and react than their carbon analogues. Indeed, the thermal decomposition of monosilane into silicon and hydrogen at temperatures above 420 °C is the industrial method of choice to produce very pure silicon layers via chemical vapor deposition.

On the other hand, these elementary characteristics are also the basis for the excellent combustion enhancing characteristics of monosilane. The strong tendency of silicon to combine with oxygen leads to rapid combustion of silanes, and even to hypergolicity, for example with air. In contrast, hydrocarbons are neither pyrophoric in air nor with other oxidizers at ambient pressure and temperature. For this reason, monosilane has been used very successfully as a combustion enhancer since decades. It has been pointed out before by various authors and recently, again by Fletcher ²⁾, that hydrocarbon combustion in supersonic flows, as is the case in scramjets, can hardly be achieved or maintained in a wide parameter range without an additional combustion enhancer and/or flame holders.

Inspired by A. Stocks book "Hydrides of Boron and Silicon" ³⁾, NACA started examinations with various highly reactive fuels which could have the potential to be the desired additives capable of starting and maintaining stable hydrocarbon combustion at extreme conditions already in the 1950s ⁴⁻⁸⁾. The motivation was not supersonic combustion alone, but also the more short-term aim of preventing flameouts in turbojet engines, as well as the vision of rocket

engines with self-igniting and restartable fuel/oxidizer propellants. They initially investigated a borohydride, $\text{Al}(\text{BH}_4)_3$, and later pentaborane (“green dragon”), trimethyl aluminum, diethyl aluminum hydride, trimethylborane, triethylborane, propylpentaborane, ethyldecaborane, and vinylsilane. It turned out at that time that aluminum borohydride is well-suited as an ignition promoter in supersonic flows and did well in ground-testing, but was never flight-tested. Later, the use of triethylborane was developed further, was flight-tested and actually was routinely used to initiate combustion in the SR-71 Blackbird airbreather. This success story is even exceeded by the use of monosilane, which started in the 1980s with hydrogen as main fuel⁹⁻¹⁹ and shortly later with HC fuels²⁰⁻²³. Continuously in use since then (in ground-testing), monosilane finally played a vital role for ignition of the hydrogen main fuel in the ground-breaking NASA X-43 scramjet flights in 2004, pushing the world record for airbreathing, hypersonic vehicles to Mach 10.

However, monosilane does also have obvious drawbacks. It is gaseous at ambient temperatures, and it is therefore necessary to store it in a bulky extra tank. In addition, although highly desirable from the point of view of combustion enhancement, monosilane also is a potential source of danger. Therefore, already in Ref. 19) the wish was expressed to “encapsulate” monosilane in order to make it more manageable and to reduce safety requirements. One possible route could be to use liquid silanes, which have been considered as fuels before²⁴⁻²⁷.

2. Thermodynamics and Kinetics of Higher Silanes

Longer-chained silanes with chemical formulae $\text{Si}_n\text{H}_{2n+2}$ and Si_nH_{2n} (cyclic molecules), where n denotes the number of silicon atoms, are high-density liquids at ambient conditions from trisilane Si_3H_8 on. With increasing chain length, the vapor pressure and at the same time the pyrophoricity at normal conditions, and thus, the risk potential, decrease. It has been pointed out before in theoretical studies²⁴⁻²⁷, that the predicted performance of the system of 100% silanes fuel with various oxidizers is similar to that of hydrocarbons, despite the much higher average mass of the combustion products, owing to Si having more than twice the mass of C. This is mainly due to the fact that the enthalpies of formation of silicon hydrides are large and positive, whereas those of the analogues hydrocarbons are strongly negative²⁴ – which means that silanes bring much more energy into the combustion system. Experimental thermodynamic data on liquid silanes are very scarce. Therefore, sophisticated *ab initio* calculations were used as a source for thermodynamic temperature-dependent data²⁸⁻³⁰ as input for the performance prediction calculations. These previously published results included Si species with up to 5 silicon atoms. In order to re-check these data, and to extend the data to species with 6 and 7 Si atoms (hexasilanes and heptasilanes), recently a new study employing various different *ab initio* approaches, including G3//B3LYP density functional theory, has been carried through and yielded thermodynamic properties in the temperature range 100-6000 K³¹. One important result of this

study is that the previous *ab initio* calculation results are in good agreement with the new study. This increases the confidence in the previous performance predictions and the ones presented within this article. Furthermore, as concerns the hexa- and heptasilanes, for which no data at all existed so far, the trend of increasing heats of formation can be confirmed also quantitatively as they are in good agreement with the incremental approximation. The heat of formation of *n*-hexasilane Si_6H_{14} ranges from $\Delta H^\circ_{f,298} = 217.1$ to 239.2 kJ/mol, and with *cyclo*-hexasilane (*cyclo*- Si_6H_{12}) from $\Delta H^\circ_{f,298} = 211.1$ to 237.8 kJ/mol. With *n*-heptasilane Si_7H_{16} , $\Delta H^\circ_{f,298} = 251.8$ to 278.3 kJ/mol, and with *cyclo*-heptasilane (*cyclo*- Si_7H_{14}) the calculated heats of formation range from $\Delta H^\circ_{f,298} = 250.7$ to 281.7 kJ/mol, depending on whether the method of atomization energies or homodesmotic reactions was used with G3//B3LYP³¹. In figure 1, the heats of formation of silanes are contrasted with those of alkanes. Also given are the main products of combustion, namely water, silicon dioxide and carbon dioxide, as well as heats of formation of other important fuels and additives such as boron compounds. It is clearly obvious that one main advantage of silanes is the high potential energy release due to their strongly positive heats of formation and the strongly negative heats of formation of the main combustion products (if these are not in elementary form such as hydrogen and silicon, for which $\Delta H^\circ_{f,298} = 0$ by definition).

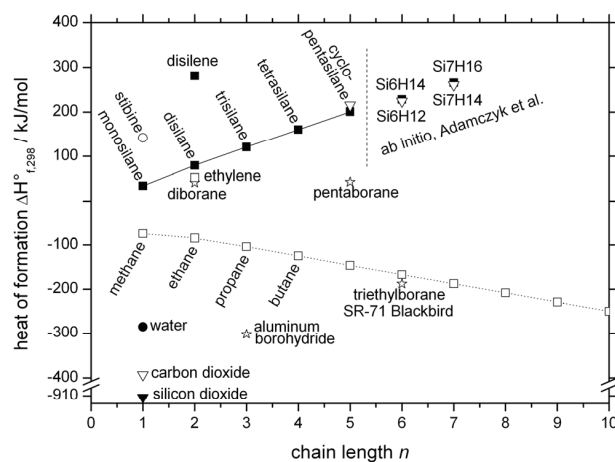


Fig. 1. Overview on heats of formation $\Delta H^\circ_{f,298}$ of various fuels and fuel additives. The chain length n denotes the number of central atoms in each species. Heats of formation of silanes are strongly positive, while heats of formation of alkanes are strongly negative.

The previous performance predictions were carried through assuming shifting equilibrium. With monosilane, this approximation is justified because it is known that monosilane kinetics are so fast that monosilane additives (in percentage of order 5-20%) actually speed up the kinetics of combustion dramatically when used as a combustion enhancer, e.g., lowering auto-ignition temperatures as well as ignition delay times by orders of magnitude both with hydrogen as well as hydrocarbon main fuels²³. However, little to no such data existed so far for higher, liquid silanes. Therefore, we started an extensive shock-tube study in order to determine the

decomposition characteristics of a liquid silane with 5 silicon atoms, namely *cyclo*-pentasilane Si_5H_{10} (CPS)³²⁾. This silane is especially well suited because it is producible in ultrahigh-purity based on organic starting substances and because of its cyclic structure. It recently received special attention because it was used in milestone experiments where large semiconducting layers were produced from the liquid CPS in an elegant way (“spray-on silicon”) ^{33,34)}, instead of using complex, time-consuming and rather inefficient chemical vapor deposition methods and gaseous SiH_4 . It shall be noted here that one main reason for this procedure to work is the convenience by which CPS can be driven to decompose into hydrogen and silicon, which then forms the semi-conducting layer. This in turn, obviously is connected to the high inner energy of liquid silanes.

The CPS samples for our shock-tube study ³²⁾ have been synthesized by an improved method based on Refs. ³⁵⁻³⁸⁾. While the analysis is preliminary and a comprehensive kinetic model is still to be developed, one core conclusion can already be drawn from the first shock-tube decomposition experiments with *cyclo*-pentasilane. Atomic Resonance Absorption Spectroscopy (ARAS) on the Si triplet transition [$4s(^3P_J) \leftarrow 3p^2(^3P_J)$] at a wavelength of $\lambda = 251.4$ nm revealed that the time-dependent occurrence of atomic Si is similarly rapid with *cyclo*-pentasilane as with monosilane. As an example, figure 2 depicts the time history of Si atom formation during the decomposition of CPS when compared to monosilane during a single shock-tube shot at a temperature of about 1700 K. Si resonance absorption rises to nearly 100 % within tens of microseconds, which is equivalent to formation of atomic silicon.

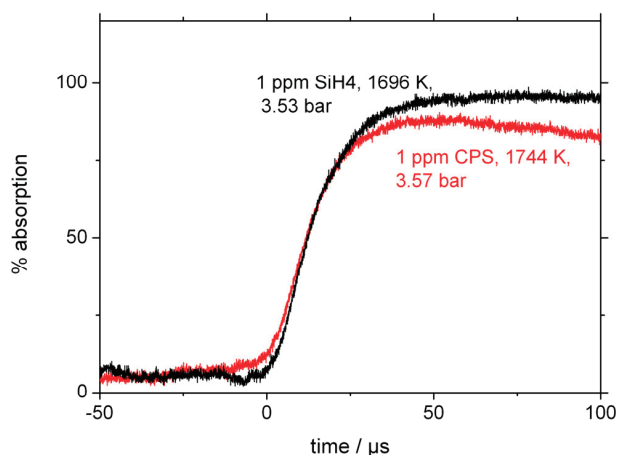


Fig. 2. Example of Si-ARAS results during decomposition of CPS and monosilane at about 1700 K. The Si formation is equally fast with both silanes.

Although only decomposition and no time-resolved shock-tube measurements of oxidation can be carried through within the present study ³²⁾, there are strong indicators that oxidation will be similarly rapidly with CPS (liquid silanes, in general) as with monosilane. First of all, it is known that atomic silicon is ultrareactive, and secondly, no detectable amounts of Si had been detected in previous shock-tube

experiments with monosilane, when oxygen was present ³⁹⁾. This was interpreted as a result of very fast oxidation of Si by O_2 with a rate coefficient close to the collision frequency ($2.0 \times 10^{14} \text{ cm}^3 \text{ mol}^{-1} \text{ s}^{-1}$). Therefore – although certainly explicit experimental confirmation is desirable – it can be concluded at this point that liquid silanes such as *cyclo*-pentasilane should offer somewhat similar combustion-enhancing capabilities as monosilane. This means that, for example, liquid silicon hydrides could be used to “spike” liquid hydrocarbons, rendering the mixtures much more reactive than conventional hydrocarbon fuels, and maybe even bring about hypergolicity.

3. Miscibility of Hydrocarbons and Silicon Hydrides

If hydrocarbon fuels are well miscible with silicon hydrides, such HC/SH fuel blends could potentially be stored in a single tank. This is therefore of paramount importance from an engineering point of view and is reviewed in this section. At first, the liquid temperature ranges of hydrocarbons, silicon hydrides and other fuels are considered. A certain overlap in liquid temperature ranges is a fundamental requirement for good miscibility, although to a certain extent it might also be possible to dissolve a gas like monosilane in a liquid hydrocarbon. The liquid temperature ranges of HC and SH fuels, as well as those of hydrazine, MMH and UDMH are summarized in figure 3.

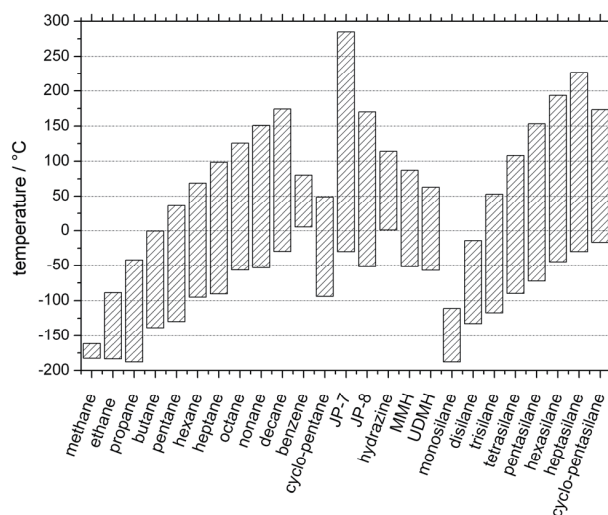


Fig. 3. Visualization of liquid temperature ranges of various hydrocarbon, silicon hydride, and standard rocket/scramjet propellant fuels. There are large overlap ranges between hydrocarbons and silicon hydrides.

As can be seen from figure 3, there are wide overlaps between hydrocarbons and silanes. For example, already the first silane which is liquid at ambient conditions, trisilane, has a wide overlap with kerosene-type hydrocarbon blends such as JP-7 or JP-8. The match between longer-chained silanes such as tetra- and pentasilane and kerosene fuels is even larger. The same holds with hydrazines. Since the liquid temperature range of methane is completely embraced by the liquid temperature range of monosilane, even a (cryogenic) mixture of methane and monosilane seems possible.

Despite these promising considerations, chemical compatibility might tell a completely different story. To the best of our knowledge, no systematic (and long-term) study of such miscibility has been carried out to date. However, certain supporting facts can be found in literature that there is a high probability of good miscibility of hydrocarbon fuels with silicon hydride fuels. In fact, the method used for preparation of the CPS samples for our shock-tube experiments actually involved dissolving CPS in benzene. Furthermore, it is reported that 2,3-dimethylbutan C_6H_{14} , monoglyme, diglyme, *cyclo*-hexane, *n*-hexane and pentane had been used as a solvent, as well as alkenes such as cyclopenten and *cyclo*-hexen, and also frigene⁴⁰⁻⁴²⁾. There is even an indication that silanes are chemically compatible with (water-free) hydrazine^{43,44)}. A limitation of miscibility comes with increasing chain length: In Ref. 40, it is reported that paraffin-like silicon hydrides with very long chain lengths $n > 15$ are not well miscible anymore in alkanes and silanes of medium chain length. However, this does not really affect the consideration of HC/SH fuel blends, because one would choose medium-chain length species (for example, because of their higher hydrogen fraction) for these applications anyway.

4. Performance Predictions with HC/SH Fuel Blends

The results of the considerations, experiments and calculations described in the previous sections strongly suggest an investigation of the performance predicted for HC/SH fuels blends by standard rocket propulsion computer codes. We use the NASA Lewis Code CEA2 as in previous publications. The chamber pressure is set to 70 bar in all cases considered for reasons of comparability. At first, we examine a mixture of the simplest HC/SH combination, namely a mix of (cryogenic) methane/silane with LOX as oxidizing agent (here, we have to postulate that methane and silane are miscible in the cryogenic state). Figure 4 a) shows the theoretical specific impulse I_{sp} obtained with methane only, silane only, and a mixture of methane with 10% silane, as well as a mixture of 50%/50% by weight. Here, the I_{sp} is plotted vs. the equivalence ratio defined as

$$\Phi = \frac{\frac{f}{o}}{\left(\frac{f}{o}\right)_{stoich}}$$

where f/o is the fuel-to-oxidizer mass ratio, and $(f/o)_{stoich}$ is the stoichiometric fuel-to-oxidizer ratio.

As already known from a previous publication²⁴⁾, where pure silicon hydrides/LOX were contrasted with pure hydrocarbons/LOX, the maximum of the specific impulse of pure methane/LOX (black curve) and pure silane/LOX (red solid curve) are nearly identical. However, the maximum is shifted to fuel-richer equivalence ratios with silane due to the high heats of formation.

When 10% silanes is added to the methane fuel (orange plot), the I_{sp} does also not change much, but it is expected that it will improve the combustion efficiency of the fuel blend. When a 50%/50% mixture (red dashed plot) is regarded, the theoretical specific impulse even increases significantly when compared to both methane and silane alone. This shows that

the specific impulse of a methane/LOX rocket engine can be increased by using substantial amounts of monosilane additives. At the same time, it is expected that the combustion efficiency will be drastically increased due to the large amounts of monosilane present in the system.

The same results plotted vs. the oxidizer-to-fuel mass ratio are given in figure 4 b). It shows that while the maximum I_{sp} is located at a value of o/f mass ratio < 1 with pure silane fuel, the maximum is found at o/f mass ratio > 1 with methane. Similarly, this is the case for the o/f volume ratio (see figure 4 c). Therefore from an engineering point of view, by adding monosilane, one can adjust the system either to optimize the I_{sp} when the tank size is the same (volume ratio $o/f = 1$) or when the weight of oxidizer and fuel is the same (mass ratio $o/f = 1$), or one can choose a tradeoff in-between.

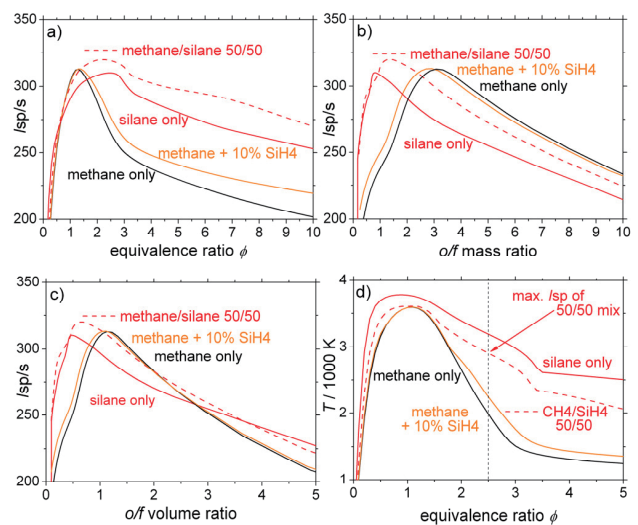


Fig. 4. Performance prediction with a (cryogenic) mixture of methane and silane with LOX. With a mixture of 50/50, a higher specific impulse is obtained than with 100% methane and silane alone.

Finally, figure 4 d) depicts the flame temperatures in the combustion chamber obtained from the calculations. Albeit the maximum temperatures are produced by silane-rich mixtures, the temperatures at those equivalence ratios where the maximum specific impulse is reached are drastically lower for the silane-rich mixtures than for the methane-rich ones. For example, while with pure methane the maximum specific impulse occurs at the same mixture ratio where the flame temperature is maximum (close to $\Phi = 1$), the maximum I_{sp} with the 50%/50% methane/silane mixture occurs at a much larger equivalence ratio of $\Phi \approx 2.5$, where the flame temperature is substantially lower. This means that a methane/silane fuel blend with a silane fraction of a few tens of percent, burned with LOX, is predicted to yield not only a significantly higher specific impulse than methane/LOX, but at the same time produces a lower flame temperature and thus lowers the heat load on the combustion chamber and nozzle walls.

Besides methane/silane mixtures, various other HC/SH fuel combinations have been examined. For example, as already indicated above, it might be feasible to dissolve a fraction of

gaseous monosilane in liquid hydrocarbon fuels, such as the kerosene type Jet-A fuel. Figure 5 a) summarizes the CEA2 calculation results for pure Jet-A fuel, Jet-A fuel with 5% of monosilane as additive, and with 10% monosilane additive, all used with LOX as oxidizing agent. As can be seen from the figure, on the one hand the maximum specific impulse would not change much by adding such moderate amounts of monosilane, but on the other hand it is likely that the reactivity of the mixture would be dramatically increased.

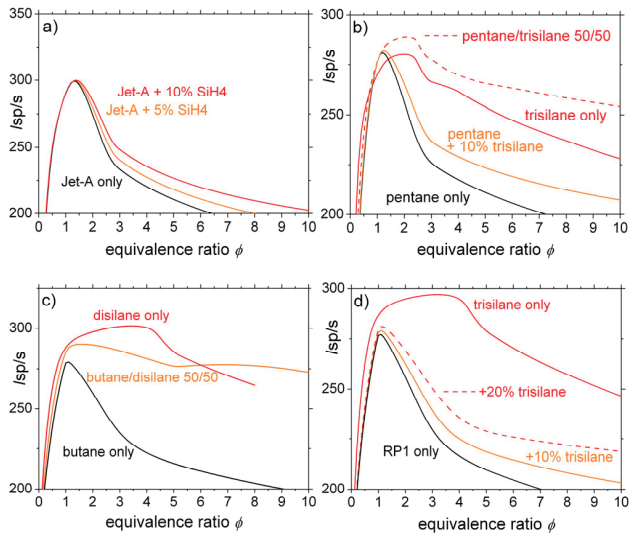


Fig. 5. Performance prediction for different HC/SH fuel blends with different oxidizers: a) Jet-A kerosene fuel + monosilane solutions, with LOX as oxidizer, b) Pentane/trisilane mixtures with NTO as oxidizer, c) Liquid butane/disilane mixtures with hydrogen peroxide, d) RP-1 fuel mixed with trisilane, and rocket grade hydrogen peroxide.

Next, a different oxidizer, namely the nitrogen tetroxide N_2O_4 , which can be stored in the liquid state relatively easily, is assumed as oxidizer of pentane and trisilane. As can be seen from figure 3, this hydrocarbon and silicon hydride have very similar liquid temperature ranges, and in addition both embrace the range in which N_2O_4 is in the liquid state. Thus, potentially, mixtures of pentane and trisilane fuel could be stored in one tank at the same temperature as N_2O_4 in the oxidizer tank. Regarding the theoretical specific impulse, our calculations reveal that mixtures of pentane/trisilane yield maximum specific impulses which are actually significantly higher than using pentane or trisilane alone (see figure 5 b). This is the same phenomenon which seems to occur with the system of methane/silane/LOX (see figure 4), and will be subject to future investigations. The same holds for the potential effect of such substantial admixtures of trisilane on the hypergolicity of such a system.

In figure 5 c), I_{sp} predictions for the somewhat exotic combination of butane and disilane with rocket grade hydrogen peroxide (RGHP, 98%) are depicted. Although the boiling points of both fuels at standard conditions are $< 0^\circ C$, it might be worth the effort to consider the combination of these fuels, because of the particularly high specific impulse predicted by CEA2.

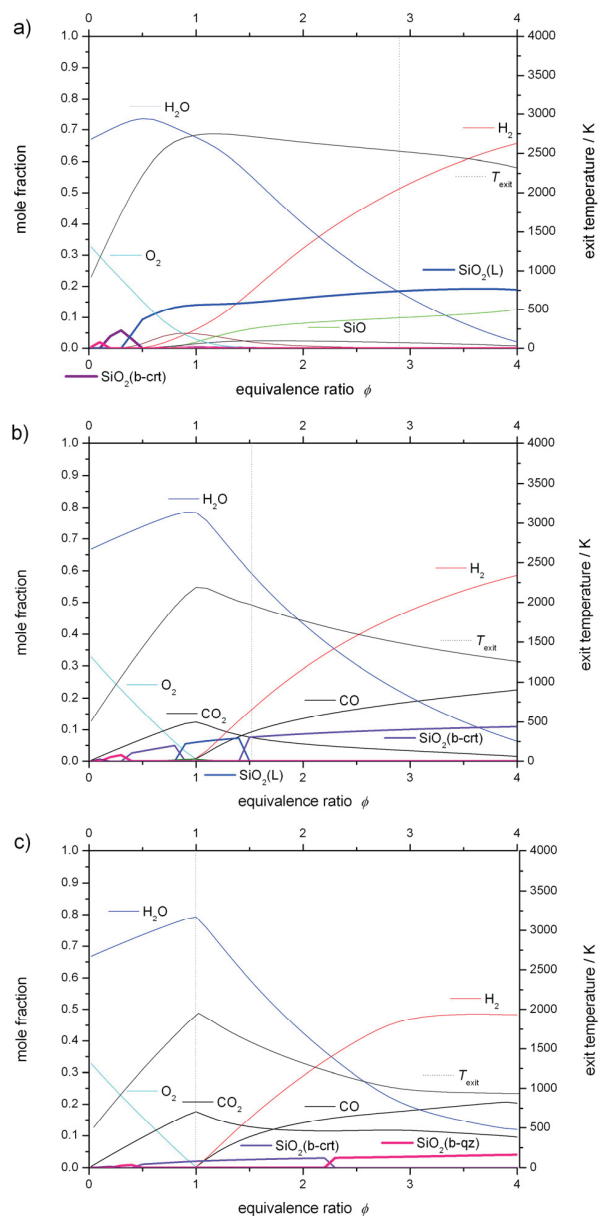


Fig. 6. Combustion products at nozzle exit with rocket grade H_2O_2 as oxidizing agent and a) pure trisilane, b) 50% RP-1/50% trisilane, and c) 80% RP-1/20 trisilane. The fraction of condensed species (mainly, SiO_2) is reduced from up to 20% with pure trisilane (a) to $< 3\%$ with the 80%/20% blend (c).

Finally, in figure 5 d), the performance of mixtures of RP-1 rocket propellant with trisilane and with RGHP as oxidizer is indicated. RP-1 and trisilane are both liquid in a large temperature range and could therefore potentially be stored in a single tank. As already reported in Ref. 26), pure silanes outperform significantly hydrocarbon fuels such as methane and pentane in terms of maximum specific impulse when used with rocket grade H_2O_2 . This again can be seen here with RP-1, the pure trisilane fuel having a substantially higher specific impulse than RP-1 rocket fuel. In this case the specific impulse increases monotonously with increasing fraction of trisilane. As we have seen, this is unlike to the case

with NTO as oxidizer, for example in case of the pentane/trisilane system in figure 5 b), and unlike than with the methane/silane/LOX system (figure 4), where the maximum I_{sp} was instead obtained with mixtures of HC/SH, the I_{sp} being lower with either pure HC or pure SH.

It is expected that already relatively moderate admixtures of silanes to hydrocarbon fuels might render this combination hypergolic with rocket-grade hydrogen peroxide (maybe also less highly concentrated hydrogen peroxide).

The generation of condensed combustion products such as Si and SiO_2 needs to be taken into account. A too large fraction of condensed species in the exhaust flow could have a significant effect on rocket engine performance. As has been seen in a previous study⁴⁵⁾, the fraction of condensed species is largest at the nozzle exit. This is understandable since the temperature is always lower at the end of the nozzle than upstream in the nozzle throat or even in the combustion chamber itself. Figure 6 a) shows the mole composition at the nozzle exit, where condensation is most prominent, using a mixture of pure trisilane/ H_2O_2 . As can be seen, here the main condensed combustion product is liquid silicon dioxide $\text{SiO}_2(\text{L})$, which reaches a mole fraction as high as about 15%. In contrast, when a mixture of 50% RP1 and 50% trisilane is used as fuel (see figure 6 b), the silicon dioxide fraction drops below 10% at those equivalence ratios corresponding to the maximum specific impulse. When only moderate fractions are used, such as 80% RP1 spiked with 20% trisilane, the fraction of condensed species drops to only <3%. In practice, this is probably easily tolerable, the more so as condensation is much weaker in the nozzle throat let alone in the chamber. This is a general principle: with all oxidizers, possible issues with condensed Si-species will decrease with decreasing silane fraction. It should be noted that moderate SiO_2 formation might even be useful, because, as already pointed out in Ref. 27), SiO_2 film deposition on the inner walls of the combustion chamber is so effective for reducing heat load on chamber walls that it actually had been purposely done before by adding Si-containing additives in rocket engines before⁴⁶⁻⁴⁸⁾.

5. Summary

The option of "burning hydrocarbon-based fuel, perhaps spiked with a combustion enhancer rather than liquid hydrogen" has recently been reconsidered by E.A. Fletcher, at NACA/NASA, who in the 1950s explored for the first time combustion enhancers for extreme burning conditions²⁾. In this article, we support this view by presenting the concept of spiking HC fuels with silanes. It is reported in the literature that a wide range of silicon hydrides is chemically compatible and soluble in hydrocarbons, so that HC/SH fuel blends could be mixed together and could be stored in a single fuel tank. The extreme combustion-enhancing capabilities of monosilane gas are known and heavily used, for example for scramjets, since nearly 30 years. The fast kinetics of monosilane and its

high heat of formation are crucial for this. Higher, liquid silanes have higher heats of formation than gaseous monosilane and higher densities than liquid hydrocarbons. First results of on-going shock-tube studies with a liquid pentasilane suggest that the decomposition kinetics of liquid silanes are similarly rapidly as that of monosilane. This allows to draw the conclusion that using liquid silanes as fuel additives could potentially improve combustion efficiency substantially and could render a HC/SH fuel blend hypergolic, dependent on the SH fraction and on the oxidizing agent used to burn the fuel blend. In addition, it has been shown that with certain mixture ratios, the obtainable specific impulse using HC/SH mixtures is higher than using the HC fuel alone with various oxidizers, including LOX, NTO, and H_2O_2 . Furthermore, potential issues with condensed combustion species such as SiO_2 can be avoided if HC/SH fuel blends are used instead of pure SH.

This concept therefore has the potential to lead to a comparably "green", hypergolic, and high-performance HC/SH fuel blend to be used in future rocket engines or scramjets. Also, it is expected that when using HC/SH fuels, any changeover would be less complicated in terms of infrastructure and material compatibility when compared to using pure SH fuels. To be applicable as a concept, liquid silanes need to be available. Trisilane, for example, which is a hydrogen-rich silane, liquid at ambient conditions and therefore well-suited to be used as fuel additive, is already available on the open market because of its increasing use in the semi-conductor industry. Recently, a new resource-effective method of producing liquid silanes has been developed which is estimated to lead to a reduction of production costs by orders of magnitude if used on a large scale⁴⁹⁾.

In the light of the huge potential of HC/SH fuel blends, it is therefore strongly recommended to intensify research on this field, for example by systematic experimental tests of material compatibility, hypergolicity etc. Compared to other fuels, very little research has been conducted so far in the (liquid) silicon hydride fuel sector.

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