Hydrogen-powered road vehicles

The health benetits and drawbacks of a new fuel

Horizon-scanning report

Gezondheidsraad **President**
Health Council of the Netherlands

To the Minister of Housing, Spatial Planning and the Environment

Subject : Presentation of horizon-scanning report *Hydrogen-powered road vehicles*
Your reference: -
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Dear Minister,

I am pleased to submit for your attention the horizon-scanning report *Hydrogen-powered road vehicles*: the first report produced by the Emerging Environmental Health issues Surveillance Committee, whose remit is to draw the attention of Government and Parliament to important health and environment-related issues, and to identify risks and opportunities in this field. In this role, the Committee not only considers new developments, but also re-examines old themes where appropriate.

Hydrogen-powered road vehicles is concerned with a new technology, which has the potential to bring considerable health benefits, such as improved air quality in urban areas. It is conceivable that hydrogen may ultimately be used as fuel in road vehicles. To date, the main focus of attention has been on hydrogen's potential as an alternative to fossil fuels, which are expected to become scarce. In this report, however, it is the health benefits and drawbacks of hydrogen that are examined. The Committee's enquiries have established that by no means all the effects of a transition to hydrogen are predictable. Much of the necessary technology still needs to be developed or perfected. Furthermore, a hydrogen supply infrastructure has yet to take shape. The possibility of using hydrogen to fuel road vehicles is now on the agenda of the proposed policy for transition to a sustainable energy economy. The purpose of such a policy would be to enable prompt intervention where necessary. A transition policy could also serve as a framework for the consideration of other possible applications of hydrogen technology and public debate on the best way of effecting transition.

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This first horizon-scanning report by the Health and Environment Surveillance Committee describes the public health implications of adopting hydrogen as a road transport fuel and identifies the issues that need to be addressed to ensure that any such changeover is realised in a medically responsible way.

For information purposes, copies of the Committee's report have been sent to your colleagues the Minister of Economic Affairs and the Minister of Transport, Public Works and Water Management.

Yours sincerely,
(signed)
Professor J.A. Knottnerus

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to:

the Minister of Housing, Spatial Planning and the Environment

No. 2008/16E, The Hague, September 29, 2008

The Health Council of the Netherlands, established in 1902, is an independent scientific advisory body. Its remit is "to advise the government and Parliament on the current level of knowledge with respect to public health issues and health (services) research..." (Section 22, Health Act).

The Health Council receives most requests for advice from the Ministers of Health, Welfare & Sport, Housing, Spatial Planning & the Environment, Social Affairs & Employment, Agriculture, Nature & Food Quality, and Education, Culture & Science. The Council can publish advisory reports on its own initiative. It usually does this in order to ask attention for developments or trends that are thought to be relevant to government policy.

Most Health Council reports are prepared by multidisciplinary committees of Dutch or, sometimes, foreign experts, appointed in a personal capacity. The reports are available to the public.

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Executive summary

Hydrogen-powered road vehicles: a vision of the future

Because of the political, social and environmental problems associated with dependency on fossil fuels, there is considerable interest in alternative energy sources. Hydrogen is regarded as a promising option, particularly as a fuel for road vehicles. The Dutch Energy Research Centre (ECN) recently published a vision of the future, in which it suggested that by 2050 more than half of all cars in the Netherlands could be running on hydrogen.

Assuming that the hydrogen is produced from renewable energy sources, migration to hydrogen-powered vehicles would also curb carbon dioxide emissions. In the United States, Japan and Europe, considerable public and private investment is therefore being made with a view to developing the technologies needed to make the creation of a hydrogen-based economy possible within a few decades.

A switch to using hydrogen as the primary energy source for road vehicles would have far-reaching social consequences. As with all technological developments, opportunities would be created, but drawbacks would inevitably be encountered as well. Some of the disadvantages associated with hydrogen are already known, and are to some degree manageable. It is likely, however, that other drawbacks would come to light only once hydrogen-powered cars were actually in use.

With that thought in mind, and in view of the social significance of a possible transition to hydrogen, it was decided that the Health Council should assess the positive and negative effects that hydrogen use could have on public health. It is particularly important to make such an assessment at the present early stage in the development of hydrogen technologies, so that gaps in existing scientific knowledge may be identified and appropriate strategies may be developed for addressing such gaps. This report has been produced by the Health and Environment Surveillance Committee, which has special responsibility for the identification of important correlations between environmental factors and public health.

From production to practical use

Like electricity, hydrogen is an energy carrier; its production therefore requires an energy source. As with electricity again, various sources can be used and production may take place at large centralised plants or small distributed units. The finished product may then be brought to the end user in tanks or by pipeline. A road vehicle would carry a supply of hydrogen in a tank, supplying either a combustion engine or a fuel cell to generate electricity for an electric motor.

Health benefits

First, the use of hydrogen as fuel for motorised road vehicles would lead to less air pollution, and thus to improved public health, particularly in urban areas. The only by-product of hydrogen combustion is water, so emissions of the harmful substances associated with conventional combustion engines, such as carbon dioxide and particulates, would be reduced. Traffic-related air pollution would not be eradicated altogether, however: a significant amount of the particulate material released into the atmosphere consists of tiny fragments of tyre rubber and asphalt, for example.

A further health benefit would derive from the fact that vehicles powered by a combination of hydrogen fuel cell and electric motor would be quieter. A general transition to such vehicles would therefore mean less noise pollution and fewer noise-related sleeping problems. Reduced greenhouse gas emissions would also have an indirect health benefit, since climate change would be attenuated and the related adverse health effects mitigated. However, any such benefit would be dependent on the hydrogen being produced by a ‘climate friendly’ process: hydrogen is itself merely an energy carrier (like electricity), so the sustainability of its use is determined by the manner of its production.

At the present time, there are two production methods that appear to be both feasible and relatively clean. The first involves the use of natural gas, which would result in modest emissions. The second entails the gasification of coal, coupled with underground storage of the unwanted carbon dioxide produced along with the hydrogen. Unfortunately, carbon dioxide storage techniques are as yet in their infancy. Nevertheless, these two methods are the most viable options pending the longer-term development of more sustainable forms of production based on the use of solar, water or wind energy. Other possibilities include biomass gasification and nuclear energy.

Adverse health effects

How might the use of hydrogen as a vehicle fuel adversely affect public health? First, hydrogen use entails fire and explosion risks. Particular attention should be given to these risks, because hydrogen does not behave in the same way as the fuels we are currently used to; any leakage of hydrogen within an enclosed space is especially dangerous. Second, the release of harmful substances from vehicle fuel cells could have an adverse effect on health. The vehicles of the future may have hydrogen fuel cells to generate power for electric motors. Such fuel cells could be associated with the release of harmful particles into the environment, not only during production and use, but also when the cells are scrapped. Unfortunately, it is not yet possible to say which materials are liable to be the most significant in relation to public health. The Committee nevertheless believes that particular attention should be given to the possible implications of the presence of nanoparticles in hydrogen storage tanks and fuel cells.

Hydrogen use might also adversely affect public health by another – very different – mechanism, namely its effect on the composition of the atmosphere and upper air strata. A switch to hydrogen-fuelled vehicles would lead to hydrogen leaks, to the emission of an uncertain amount of greenhouse gas and to an uncertain reduction in the emission of substances such as nitrogen oxides and carbon monoxide. These developments are liable to have implications for the troposphere and stratosphere, and thus for our climate and the ozone layer, but their precise influence is hard to predict. Modelling suggests that the net impact could be positive or negative, and scientific opinion on the influence of hydrogen remains divided.

The known risks should be manageable to some degree, partly by drawing on experience with the industrial use of hydrogen and experience in the field of waste management and recycling. However, the introduction of hydrogen technology is also likely to be accompanied by currently unforeseen risks. It is therefore advisable that any such introduction should be incremental and carefully monitored with a view to picking up the signs of any problems as early as possible.

The need for control

The far-reaching consequences of adopting hydrogen technology necessitate monitoring and control. At present, the focus is mainly on the possible environmental benefits, and relatively little attention is being given to the potential hazards. However, if a transition is to take place, the entire spectrum of effects should be considered, insofar as they may be predicted.

In this context, the government has an important coordinating role to play. The sustainability of the production methods and the way in which an infrastructure is realised will be key issues. Systematic consideration needs to be given not only to the implications for the economy and the local and global environment, but also to the public health effects (which will be influenced by the economic and environmental effects). Public support is vital if a successful transition is to be achieved.

With careful transition management, the consideration of health implications can become an integral part of the processes of developing and introducing hydrogen technology. In this way, any adverse health effects can be identified in good time and appropriate corrections made. Furthermore, such a strategy will enable verification of the anticipated health benefits.

The Committee therefore favours an incremental approach to the adoption of hydrogen technology, in the context of a democratic process. While the outcome of that process cannot be predicted, the Committee is confident that the advocated approach would enable the sensible management of unforeseen hazards, and the optimal exploitation of unforeseen opportunities, involving, for example, more sustainable forms of mobility.

Chapter **1**

Introduction

1.1 Are hydrogen-powered vehicles the future?

Possible alternatives to fossil fuels are very much in the spotlight. The interest is due not only to the finite nature of the world's accessible reserves of coal, gas and oil, but also to the general desire to reduce emissions of greenhouse gases.[1] One of the alternatives is hydrogen. Pure hydrogen is not found in nature, but it can be obtained from raw materials such as water and hydrocarbons. The use of hydrogen as a fuel would facilitate the management of carbon dioxide (CO_2) emissions, although the emission reduction actually achieved would depend on the hydrogen production method adopted. However, a reduction in CO_2 emissions is not the only benefit potentially attainable. Switching to hydrogen would also mean less traffic-related air pollution. The American Academy of Sciences described the expectations for hydrogen thus:[2]

> The vision of the hydrogen economy is based on two expectations: (1) that hydrogen can be produced from domestic energy sources in a manner that is affordable and environmentally benign, and (2) that applications using hydrogen – fuel cell vehicles, for example – can gain market share in competition with the alternatives. To the extent that these expectations can be met, the United States, and indeed the world, would benefit from reduced vulnerability to energy disruptions and improved environmental quality, especially through lower carbon emissions.

People have expressed many different expectations regarding the impact of adopting hydrogen as a fuel. However, no one knows how realistic these expectations are. Although the principle of using hydrogen as an energy carrier is well-established, the gas has never been utilised on any significant scale in the transport sector. The necessary technology is under development, but it will be several decades before we know for certain whether that technology will reach maturity or whether its application in road vehicles is practicable.[1,2,3]

The adoption of hydrogen as an energy source for road transport would have far-reaching implications for our society. It would be necessary to create additional production facilities, for example, and either to establish a new distribution structure or to overhaul the existing networks.[1,2] That would result in major economic realignments in the energy sector. People would also need to switch to hydrogen-powered vehicles, and a whole new system of safety regulations and procedures would be needed.

Despite the question marks over the viability of this new technology, considerable sums are being invested, both in Europe and elsewhere, with a view to making hydrogen available as an energy source for the transport sector and possibly other sectors by the middle of this century.[4] The ECN's energy vision[*] suggests that more than half of all cars in the Netherlands could be running on hydrogen by 2050.[5]

1.2 Issue

There is often considerable initial optimism regarding the potential benefits of new technologies.[6,7] In many cases, it is not until the technology enters widespread use that the associated advantages can be properly judged, or that the disadvantages become apparent. Not only may the benefits prove to be smaller than anticipated, but unexpected drawbacks may also come to light. Consequently, as the tempo of development quickens and the impact of technology increases, it is ever more important to assess the likely implications of a new technology at the earliest possible juncture.[8,9]

Against this background, the Emerging Environmental Health issues Surveillance Committee was asked by the Council's president to explore the public health implications of moving over to the use of hydrogen as a fuel for road vehicles. The possibility of using hydrogen as an energy source for other purposes, such as domestic heating[10] or powering aircraft[10,11], and the public health implica-

* Energy Research Centre of the Netherlands, Petten.

tions of doing so, fall outside the scope of this report. In this horizon-scanning report, the Committee addresses the following questions:

1 What public health benefits would accrue from using hydrogen as a road transport fuel?
2 What public health risks would such use bring?

1.3 Remit of the Emerging Environmental Health issues Surveillance Committee

The remit of the Emerging Environmental Health issues Surveillance Committee is to draw the attention of government and parliament to important health and environment-related issues, and to identify risks and opportunities in this field. In this role, the Committee not only considers new developments, but also re-examines old themes where appropriate. The Committee presents its findings in horizon-scanning reports, in which the latest scientific insights are discussed and advice is given regarding the need to place the relevant topic on the policy agenda. The Committee's mandate is for two years and is due to expire on 22 October 2009.

1.4 Methodology

In consultation with several Committee members, the Health Council secretariat prepared various texts for this report, which were then discussed at meetings of the Committee. The full draft report was subsequently submitted for review to the Council's Standing Committee on Health and Environment. In addition, Professor CHJ Midden, Professor of Culture and Technology at Eindhoven University of Technology, was asked to comment on the draft.

1.5 Structure of the report

Section 2 describes the technology needed to utilise hydrogen as an alternative energy source and identifies the technical obstacles to the development of that technology. In section 3, the Committee presents a survey of the public health benefits likely to accrue from using hydrogen as a transport fuel. Section 4 reveals the other side of the coin: the public health risks associated with such use. Finally, section 5 sets out the Committee's principal conclusions and recommendations regarding the monitoring of future developments in this field.

Chapter 2

Hydrogen as a road transport fuel

2.1 Potential and obstacles

Hydrogen technology is seen as a promising means of facilitating progress towards a cleaner and more sustainable energy economy in the course of this century.[1,2,10] Hydrogen represents a clean energy option for transport, industry and household applications, because the only by-product of its combustion in air is water. Many commentators therefore foresee the transformation of our existing oil-based economy into a hydrogen-based economy, i.e. an economy in which hydrogen is the primary energy carrier. This vision of the future is not a new one. In the 1970s, it was predicted by some that the changeover would already have taken place by now. Clearly, those predictions have not come to pass. Nevertheless, although technical and economic obstacles exist, the adoption of hydrogen as an energy source remains a serious option.[1,5,12] Indeed, various observers still expect hydrogen to make a telling contribution to the creation of a sustainable energy economy.[1,13]

The interest in hydrogen technology is driven mainly by two imperatives: to end our dependency on oil products and to reduce the production of greenhouse gases.[1,2,14] However, much of the technology needed to create a hydrogen supply infrastructure has yet to be developed or perfected. Nor is it clear what principle forms the most appropriate basis for the design of a large-scale infrastructure: should production, storage and distribution be organised around large centralised systems, or is it better to work with small dispersed units? It is also clear that transition to a hydrogen-based economy would have complex and far-reaching social and economic implications.[1,2,14-16]

In certain quarters, practical steps towards the use of hydrogen in road vehicles are already being taken. Several car manufacturers have prototype hydrogen-powered vehicles, and trials are underway in various parts of the world.[17-19] Amsterdam's public transport operator has participated in a European project, for example, in which experience was gained with the use of hydrogen-powered buses.[20] The results of this project are currently being evaluated, but it appears that from a mechanical perspective there are few real problems.

2.2 From production to use in road vehicles

On the following pages, the Committee examines the technological aspects of the production and distribution of hydrogen and its use in road vehicles. The 'well-to-wheel' chain and its three primary links are illustrated in Figure 1.

2.2.1 The production of hydrogen

Under normal conditions, hydrogen is a gas. Unlike, for example, natural gas, it does not occur naturally in substantial quantities. It therefore has to be released from compounds such as water and hydrocarbons. In that respect, hydrogen differs from fossil fuels: it cannot be extracted straight from the ground. Further-

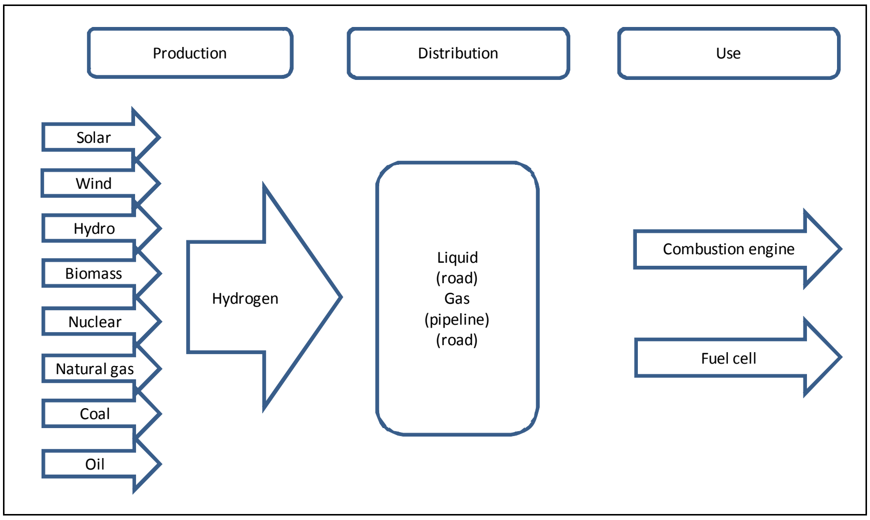

Figure 1 The hydrogen use chain: from well to wheel. Following [21].

more, the separation of hydrogen from the compounds in which it occurs requires energy.

Because hydrogen requires production, it is regarded as an ‘energy carrier’. In that respect it is akin to electricity. A carrier is a medium for the conveyance of energy from the point of production to the point of use. The production of hydrogen is illustrated in figure 2. As the figure shows, there are various ways of producing hydrogen. It can be released from water by electrolysis, for example. Thermal processes (involving the addition of steam or oxygen, depending on the application) can also be used to produce hydrogen from water or from natural gas or coal (or, theoretically, from biomass or oil). As an alternative to the use of carbon-based fuels, wind, solar, nuclear or hydro energy can be harnessed for hydrogen production.

Various alternative energy technologies that might be utilised for the production of hydrogen are still under development, including the generation of electricity by harnessing the chemical potential difference between fresh water and saltwater.[22] Another possibility that is being investigated is biological hydrogen production using bacteria or algae.[23]

Using existing natural gas-based production technology, it is possible to achieve an energetic efficiency of roughly 85 per cent.[1,24] In other words, 15 per cent of the energy-content of the natural gas is lost in the production of hydrogen. The other existing production methods are less efficient.

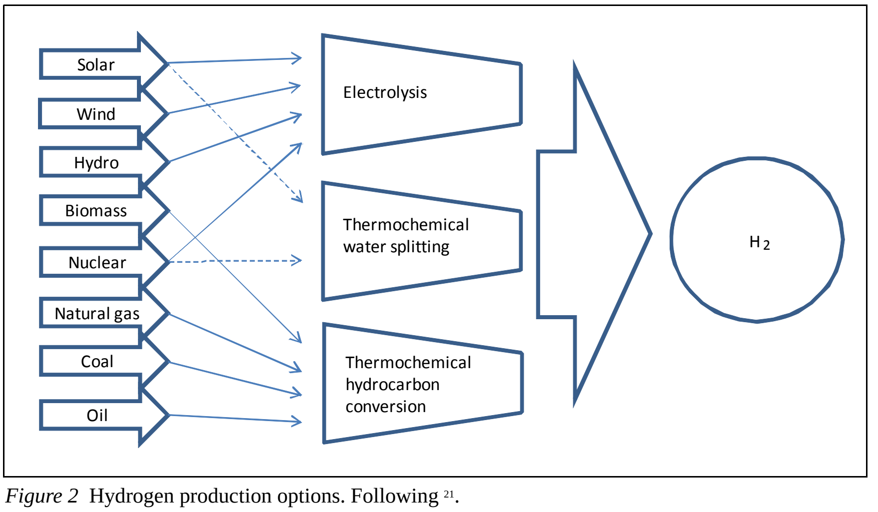

Figure 2 Hydrogen production options. Following [21].

The various production methods differ in their global climatic sustainability. The use of raw materials such as coal or natural gas would necessitate capture and storage of the resulting carbon dioxide, otherwise the changeover to hydrogen would bring no reduction in greenhouse gas emissions.[25] The most sustainable methods of hydrogen separation – i.e. the methods that result in the least emission of greenhouse gases – are those based on biomass or hydro, solar or wind power. The harnessing of nuclear energy would also involve very little greenhouse gases emission.[26]

In view of the availability of coal and the associated technical possibilities, coal gasification combined with large-scale underground carbon dioxide storage would seem to be an obvious short-term production option. Other near-horizon alternatives include the extraction of hydrogen from natural gas and the gasification of biomass.[3,27] The extent to which the adoption of hydrogen as a fuel for road vehicles would in fact mean a clean and sustainable energy supply system depends to a considerable extent on the production process used.

2.2.2 *Distribution and storage*

Once produced, hydrogen would need to be transported to the end users. This would present problems, since hydrogen has a number of complicating properties. It is the lightest gas that exists, for example. Furthermore, the energy-content per unit volume of gaseous hydrogen (at room temperature and normal outdoor pressure) is about three thousand times less than that of liquid petrol.[3,28]

For storage and transportation, hydrogen therefore needs to be greatly compressed. However, compression costs energy and therefore diminishes energetic efficiency. An alternative is to liquefy the gas. Hydrogen becomes liquid at 20 K (-253 °C, see Annex B). However, that degree of cooling would mean expending roughly 30 per cent of the energy carried by the hydrogen. It would also imply the extremely efficient insulation of storage tanks to prevent additional energy losses. Cooling is therefore an energy-intensive option. Transmission by pipeline would necessitate initial compression and – with a pipeline of any significant length – the use of energy to power the compression stations needed to maintain the pressure along the route.[29]

Provided that the applicable conditions could be met, hydrogen could be transported in gaseous or liquid form by tanker truck or rail tanker, or in gaseous form by pipeline. Europe already has an extensive network of pipelines for the transmission of hydrogen gas (see, for example, Figure 3).

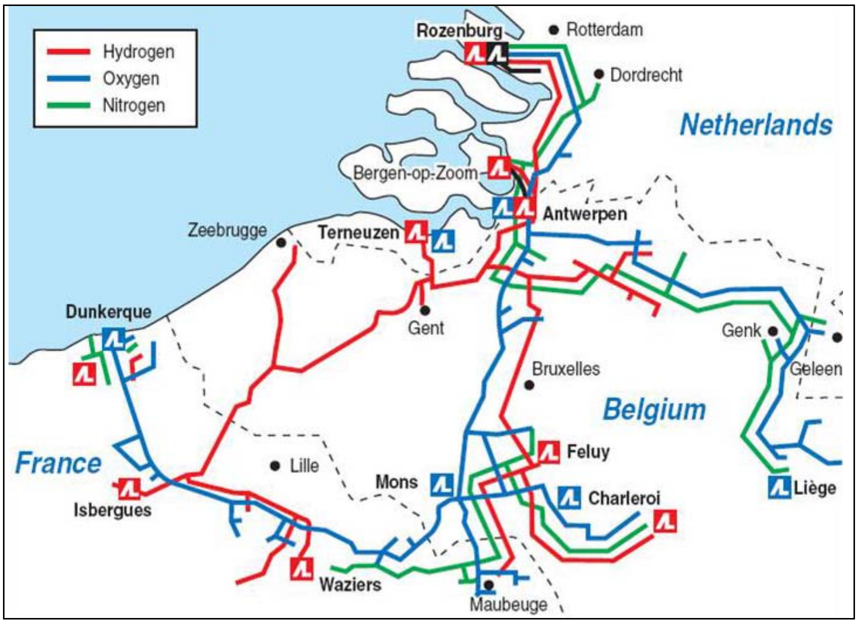

Figure 3 The Air Liquide pipeline network in north-west Europe.[31]

Choosing between long or short supply lines

In view of hydrogen's properties, one important issue influencing the design of a hydrogen distribution infrastructure is whether efficiency and safety are best served by a model based on large production plants and long supply lines, or one that features numerous well-distributed small production units and therefore short supply lines.[30] The latter option would be more expensive than the former.[29] The ultimate choice will depend partly on other (e.g. stationary) applications. Where the Netherlands is concerned, that may tend to support the use of the natural gas grid.

2.2.3 *Use in vehicles*

Storage of hydrogen in the vehicle

The energy that hydrogen contains can be harnessed by two mechanisms: directly, by means of combustion, or indirectly, by means of processing in a fuel cell to generate electricity, which is then used to power the vehicle. Whichever option is chosen, it is necessary to store hydrogen in the vehicle. Carrying a supply of hydrogen is more technically challenging than carrying a supply of a conventional fuel.

Most of the prototype hydrogen-powered vehicles developed so far have carried hydrogen under compression. Typically, the gas is stored in a tank with a rated pressure of 700 bar. This very high level of compression is necessary for the vehicle to carry sufficient fuel to have a reasonable travel range.[30,32] However, it implies not only the expenditure of considerable energy to compress the hydrogen, but also the use of tanks that are much stronger and heavier than for example an LPG tank. Furthermore, hydrogen cannot be stored in steel tanks, because it has a serious detrimental effect on the strength and integrity of that metal. The use of carbon fibre might be a viable option, and other possibilities are being seriously investigated.

Alternative ways of storing hydrogen for use in vehicles include storage (adsorption) in metal structures (metal hydrides) and storage in carbon nanotubes.[33] Unfortunately, however, the latter forms of storage currently remain very inefficient. Present-day metal hydride tanks are three times as large and four times as heavy as a petrol tank with a similar capacity. Meanwhile, the amount of hydrogen that can be stored in nanotubular structure is currently very small. Moreover, both storage techniques require high levels of pressurisation. And the problems do not stop there: the hydrogen mobilisation rate associated with the tanks is poor and the materials present major recycling challenges.

Conversion of stored energy into motion

The most straightforward way of converting hydrogen's chemical energy into kinetic energy is by processing in a fuel cell to generate electricity, which is then used to drive an electric motor. It is worth noting that fuel cell technology is not specifically a hydrogen-utilisation technology; fuel cells can also generate electricity from hydrocarbons, such as alcohol.

Numerous types of fuel cell have been developed, including cells for use in sectors other than transport. One of their great advantages is their reliability, which is attributable to the absence of moving parts. To date, this has made fuel cells an attractive option for use in remote locations, such as weather stations and spacecraft. However, for large-scale use in vehicles, the cost of the anode and cathode materials is an obstacle.

Vehicular application also implies a supply of oxygen (in the form of compressed and de-moisturised air), in order to process the hydrogen in the fuel cell. This compromises the energetic efficiency of the fuel cell. Current designs achieve an efficiency of no more than 50 per cent. This is nevertheless better than existing internal combustion engines running on oil products, which typically have an efficiency of around 30 per cent. It is also better than hydrogen-fuelled internal combustion engines, which are generally no more efficient than their oil-fuelled equivalents.

2.3 Looking to the future

Whether and to what extent the new technology is likely to secure a market share are not issues addressed by this report. However, the point should be made that hydrogen's market penetration depends on numerous factors: the needs of various population groups, the availability of alternative technologies, the extent to which other technologies develop at a similar rate, collaboration amongst market players, intervention by the government, public acceptance, etc.[34]

> Fuel cells and alternatives
>
> Because of their efficiency advantages over conventional internal combustion engines, fuel cells are currently the main focus of development. In Japan, the USA and Europe (see, for example,[17]) large sums are being invested with a view to creating vehicles with improved fuel cells incorporated into electric motors. At the moment, there are no viable alternatives to the fuel cell. On their own, batteries do not appear to be suitable for vehicle propulsion because of the low energy density and the high cost per kilowatt-hour. Nevertheless, a great deal is being invested in the development of batteries that utilise nanotechnology, and numerous car manufacturers have formed alliances with battery manufacturers (see, for example,[35]). General Motors and Daimler Benz have already announced their intention to launch electric models (see, for example,[36]). If major progress is made in the storage of electricity in batteries (or other storage media, such as capacitors; see[37]), electricity could become a serious competitor to hydrogen in the automotive sector. One of the big attractions of using electric power is the high energetic efficiency of the well-to-wheel process. Furthermore, a migration to electric-powered vehicles would not necessitate expensive new infrastructure. However, electricity and hydrogen should not necessarily be seen simply as competing options: they could possibly be used together in hybrid vehicles driven by both fuel cells and batteries.

Even if hydrogen does become the predominant energy source, various scenarios for the future suggest themselves. These scenarios differ in terms of the production, distribution and usage methods adopted, as outlined above. In this context, the Committee would point to a British project, in which several scenarios were compared.[38] The analysis performed by the British researchers indicated that the market penetration of hydrogen will depend on the introduction of applications other than road transport.

Chapter 3

Public health benefits

The use of hydrogen as an energy source for road transport would have various benefits. The two most obvious are a reduction in air pollution and a reduction in greenhouse gas emissions. Less air pollution would have direct public health benefits, since levels of exposure to the harmful substances contained in exhaust gases, such as soot, other particulates, nitrogen oxides, carbon monoxide and benzene would be cut. The health implications of lower greenhouse gas emissions would be indirect, but would also be positive. Furthermore, the use of fuel cell-powered or electric vehicles could mean less traffic-related noise annoyance.

3.1 Reduced air pollution

The use of hydrogen to fuel motorised road vehicles would clearly have a positive effect on levels of air pollution (see, for example,[39]). The emission of harmful substances such as nitrogen oxides and particulate would be cut, since the processing of hydrogen in the vehicle would result merely in the production of water.

It should not be supposed, however, that a switch to hydrogen would eliminate traffic-related air pollution. Particles from tyres and asphalt would still be released into the atmosphere, for example.[38] Furthermore, the benefits of reduced particulate emissions could be partially offset by the so-called rebound effect. If car driving were perceived to be less environmentally harmful, people might see less reason to limit their travel or to use alternatives such as public transport, particularly if consideration for the environment was not firmly established. Hence, the introduction of hydrogen technology could lead to growth in private car travel and therefore to more road, tyre and engine wear. Nevertheless, the Committee anticipates that people in urban areas would benefit from improved air quality.

Hydrogen technology could also be a public health boon for countries that are still undergoing rapid industrialisation.[40] Transition to hydrogen relatively early in the industrialisation process may be expected to avert much of the health damage associated with rapid growth in car use. Whether these benefits are actually obtained depends of course on the viability of hydrogen technology.

3.2 Reduced greenhouse gas emissions

A reduction in the amount of greenhouse gas released into the atmosphere would also be beneficial to public health, although the benefits would be indirect and apparent at the global level. Debate on ways of brining down emissions has been ongoing for some time. Low-emission energy sources, such as solar, hydro and wind energy and possibly nuclear energy and biomass, can play a role in this context.

As previously indicated, the hydrogen production method adopted would have a major bearing on the sustainability of hydrogen technology. Any production method that involves the use of fossil fuels is at odds with the objective of reducing greenhouse gas emissions. One way of getting around this would be to link the production of hydrogen from fossil fuel with safe carbon dioxide storage (the carbon capture and storage strategy).[25,41] However, the storage of carbon dioxide is not without risk.[42] Consequently, such a strategy would need to be seen as a stepping stone en route to a sustainable energy economy, which is preferable from a public health viewpoint to the continued use of fossil fuels in road vehicles.

3.3 Reduced noise annoyance

Vehicles powered by fuel cell-driven electric motors would be quieter than existing vehicles. This too would have health benefits. The Health Council has previously published a great deal of information on the influence of noise exposure on health.[43,44] However, the benefit could conceivably be partially offset by a rise in traffic accidents in which the silent approach of a vehicle was a factor. On the other hand, there is evidence to suggest that, when the traffic landscape changes, accidents fall (at least temporarily), so it would be a mistake to assume that the introduction of much quieter cars would mean more road casualties.[45,46]

Chapter **4**

Public health risks

As well as bringing public health benefits, the adoption of hydrogen as a road transport fuel could have adverse effects on public health. Most of the direct risks would stem from the storage of hydrogen in vehicles: hydrogen fires and explosions resulting from traffic accidents and leaks, and exposure to materials from fuel cells and storage tanks following accidents. When hydrogen-powered cars are scrapped, the presence of such substances could also lead to environmental pollution and thus to indirect adverse health effects. Atmospheric changes brought about by leaks of hydrogen during production, distribution and use might also pose indirect risks. However, because it is not yet known what technology will be used or what form the hydrogen supply infrastructure will take, it is not yet possible to predict exactly what the risks will be.

4.1 A cautious approach to introduction

Considering the possibility of risk migration and looking out for early warnings

When new technologies are developed, at first the focus is often only on the anticipated benefits.[6,7] The purpose of development is, after all, to meet the real or presumed needs of society. Inevitably, though, a new or modernised technology also has its drawbacks. In many cases, these involve risks of a previously unencountered kind, which are not easily predicted and may not become apparent – at least in scale – until after the technology has entered use. The emergence of such new risks in place of old ones is referred to as risk migration.[47*]

Understanding of side-effects consequently lags behind technological development. To minimise this time lag, it is advisable to assess the adverse effects of a technology as accurately as possible at the outset. Hence, it is important to consider the health implications of moving to a hydrogen-based economy well ahead of any large-scale introduction of hydrogen technology.

However, because it is not possible to predict all possible risks, society also needs to monitor post-introduction effects and to be on the lookout for early warnings.[7,48**] Even if by that stage significant experience has been acquired with the technology, the actual transition to a hydrogen-based economy would involve an increase in the scale of application, potentially bringing previously undetected problems to the fore.[7,49]

Estimating long-term risk

When considering the possible risks associated with a technology, the Committee cautions against restricting consideration to the introduction and initial application of that technology. Difficult though it may be to look into the further future, it is important to take account of the fact that, as indicated above, the drawbacks of an innovation may manifest themselves only once the technology is in widespread use or in the later stages of the life cycle of a technological application.[50] Examples include the difficulties associated with waste from nuclear power plants and the problems caused by people throwing out old mobile phones with their household waste.

Generally speaking, therefore – and certainly in this case – it is advisable to take a life-cycle oriented approach. This involves exploring at the earliest possible stage the health risks associated with each phase of production and use when assessing the value of a raw material to the economy. Such an approach provides the best possible basis for the estimation of risk.

Where several options exist, the risks associated with each option need to be examined. If, for example, distinct technologies, such as hydrogen use and biofuel use, need to be compared, various scenarios need to be considered.[51] Where hydrogen is concerned, it is important to study the implications of the various

* The cited article highlights the case of polybrominated compounds. In order to reduce the risk of burns, some clothing and electronic goods are impregnated with these substances. In the end, however, they find their way into the environment in waste, where it appears they constitute a risk to human health and an environmental hazard.

** In its recent report *Prudent Precautions*, the Health Council considered this issue in more detail, in the context of application of the precautionary principle.

production methods, because the health risks associated with hydrogen technology depend to a significant extent on whether hydrogen is produced using electricity generated at, say, a solar installation or a coal-fired plant.

When seeking in advance to build up as complete a picture of the risks as possible, it is not sufficient to consult only technologists. All stakeholders need to have the opportunity to voice their expectations and concerns in relation to the development and introduction to society of a new or modified technology. Such an approach is integral to the process of risk governance.[52*]

4.2 Acute fire and explosion risks

So, what risks does it currently seem likely that the large-scale introduction of hydrogen as road transport fuel would bring? Perhaps the most obvious is an acute risk of fire or explosion.[53]

In daylight, pure hydrogen burns almost invisibly, emitting very little thermal radiation in the process.[**] Consequently, a hydrogen fire can be difficult to detect at first, yet it has the capacity to cause injury and to spread unnoticed. However, this issue can be addressed by mixing trace gases that burn with a coloured flame and have a readily perceptible smell (as with natural gas).[49]

Another of hydrogen's properties that is potentially dangerous is that it is flammable or explosive when mixed with air in a very wide range of concentrations; most other fuels are only flammable/explosive within a narrow range of concentrations (see Figure 4 in Annex B). As a result, even a small leak in an enclosed area can create an explosion or fire risk in a production, distribution or usage setting. Hence, the use of gaseous hydrogen almost inevitably entails some level of fire and explosion risk. Coupled with hydrogen's ability to permeate the fabric of various materials, such as steel and plastics, hydrogen is technically speaking a difficult gas to handle.

Extinguishing a hydrogen fire is no straightforward matter. Indeed, a hydrogen fire should not be extinguished at all unless absolutely necessary, because it can create a risk of spontaneous explosive re-ignition. It is better to cut off the supply of the gas and let the fire burn itself out. If hydrogen became a prominent

* In this context, 'governance' means the structures and processes for collective decision-making, involving both governmental and private bodies and actors. In modern society, decisions can no longer be imposed by the government from above, but have to be developed within stakeholder networks. Where this philosophy is applied to risks and risk-related decision-making, the result is risk governance. The Health Council's recent advisory report on the precautionary principle (2008/18) considers the question of risk governance in detail.

** Some of hydrogen's principal properties are listed in Annex B.

vehicle fuel, this information would need to be made known to the fire services, pump operators and drivers.

Risk control options

Sufficient knowledge of and experience with the use of gaseous hydrogen already exists to support a tentative quantification of the fire and explosion risks likely to attend the introduction of hydrogen as a road fuel.[10] The figures suggest that, while it should be possible to meet the quantitative environmental risk criteria that apply in the Netherlands, effort does need to be made to keep the risks as low as reasonably achievable (as required under the ALARA risk policy principle[54*]). To that end, for example, attention needs to be given to safe facility design, the use of trace gases and the application of clear regulations. Furthermore, the users (including the general public) need to be made familiar with the applications of gaseous hydrogen, so that the risks – with leaks in enclosed spaces chief amongst them – can be managed effectively.

NASA's experience shows, however, that risk management is no sinecure.[55] One in five of the agency's industrial accidents involving hydrogen involved leaks that were not detected, despite the special training given to personnel, extensive procedural documentation and the presence of detectors.

There is no consensus in the literature as to whether hydrogen constitutes a greater hazard than other fuels, such as LPG, methanol or propane. The reason being that the nature and extent of the risks depend largely on the usage modalities, such as distribution system design.[32]

4.3 Pollution from fuel cells and fuel tanks

The use of metals and other compounds in vehicle storage tanks and fuel cells represents another source of risk. The release of such substances would be possible in the event of fire or explosion-related accidents. Hence, as well as having direct consequences, fuel cell accidents could have indirect adverse health effects.

The nature and seriousness of those risks will depend on the type(s) of fuel cell and fuel tank that enter general use in a future hydrogen-based economy. Different types of fuel cell use different electrolytes, which can have an adverse effect on human health. Potassium solution, for example, can burn the skin, while sulphuric acid can form a toxic vapour in the event of fire and cause burns.

* ALARA: As Low As Reasonable Achievable

Another consideration is that the existing generation of fuel cells contain heavy metals, such as platinum, which is used for the electrodes. However, the cost and relative scarcity of certain heavy metals are such that developers are energetically investigating the alternatives. One option might be to use carbon (possibly formed into nanostructures) as a carrier material for the heavy metals, thus reducing the amount of metal needed. This could have health implications, since free nano carbon particles can be harmful if inhaled.[52,56]

The use of fuel cells and fuel tanks therefore requires further attention before a sustainable position is reached. It is important to ensure that harmful substances do not find their way into the environment. To that end, it will be necessary not only to minimise the risk of incidents, but also to develop a policy for the responsible disposal of fuel cells at the end of their working life.

4.4 Atmospheric changes

A particular point of concern is the atmospheric influence of escaped hydrogen.[57,58] In the atmosphere, hydrogen reacts with so-called 'OH radicals', which play an important role in atmospheric cleaning functions, such as the breakdown of methane. Because of the complexity of the chemical reactions that take place in the troposphere and the stratosphere, it is hard to predict what the net impact on, for example, the greenhouse effect or the thickness of the stratospheric ozone layer would be. The outcome will depend on factors such as the influence of the reduction in nitrogen oxide and carbon monoxide emissions associated with the use of fuel cells, as well as the volumes of greenhouse gases and other substances released in the context of hydrogen production and construction of the hydrogen infrastructure. Furthermore, opinion differs regarding the values that should be assigned to certain key parameters used for impact modelling, such as the amount of hydrogen lost in the chain linking production and use.[59-62]

Despite the concerns outlined above, the Committee is not inclined to believe that the health benefits of adopting hydrogen as a road fuel would be negated by its atmospheric effects.

4.5 Pollution from unregulated production

If hydrogen were to enter large-scale use as a fuel, it is reasonable to anticipate the development of a price-driven global market.[63] People in any country would be free to start producing hydrogen by any means of their choosing; in some places, hydrogen might for example be produced from coal, without any carbon dioxide capture and storage arrangements. Theoretically, countries with lax environmental regulations could become bulk producers of cheap but environmentally malign hydrogen for global consumption. Such a development would negate the environmental and health benefits of using hydrogen. Prompt consideration therefore needs to be given to ways of preventing the realisation of such scenarios. One possibility might be a certification system for hydrogen production, combined with international treaty arrangements.

4.6 Reduced road safety due to quieter vehicles

Cars with electric motors are quieter than cars with internal combustion engines. One potential drawback associated with the widespread use of these quieter cars could be more road traffic casualties. However, as indicated in section 3, there is also evidence to suggest that, at least to begin with, the adoption of a new technology could bring downward pressure to bear on casualty statistics. It cannot therefore be assumed that electric cars would mean more people killed and injured on the roads.

Chapter 5

Monitoring

In this final section of the report, the Committee summarises the content of the previous sections before presenting its recommendations concerning management of the development of hydrogen technology. In this context, it is particularly important that the government monitors the situation carefully and acts to ensure that the public health benefits of hydrogen use prevail.

5.1 Public health benefits and drawbacks

The use of hydrogen would cut air pollution, especially in urban areas, by reducing emissions of the combustion products of petrol, diesel and gasoline. Fuel cell-powered vehicles would also be quieter, so noise-related problems would diminish.

The extent to which greenhouse gas emissions would be reduced, thus bringing further indirect health benefits, depends largely on the production method adopted. If, for example, coal were used to produce hydrogen on a large scale, considerable volumes of carbon dioxide would be released. That would imply capture and storage to prevent or at least minimise emissions. However, the necessary technology has yet to be perfected and entails its own risks. In other words, transition to hydrogen does not necessarily imply a climatically sustainable means of fuelling road vehicles; the potential environmental benefits would be secured only if certain conditions were met.

While bringing health benefits, the adoption of hydrogen as a road transport fuel would bring certain risks. Some of the potential problems are already known, because hydrogen has been widely used in the chemical industry for some time. The most obvious risks are fire and explosion. The particular properties of hydrogen would necessitate special steps to minimise and manage these risks. Even so, it is hard to predict how the risks would play out in the event of large-scale hydrogen use in non-industrial settings.

Another issue is the possibility of effects on the atmosphere and upper strata. It is inevitable that some hydrogen would escape during production, distribution and use. However, it is hard to say what impact the lost hydrogen would have or what the net result is likely to be.

History has shown that every new technology opens up unforeseen opportunities, but also brings with it unexpected risks – risks which may not become apparent until long after the technology has become established. The Committee sees no reason to suppose that a similar pattern of opportunities and risk would not follow in the wake of hydrogen's introduction to the road transport sector.

5.2 The need for public support

If a technology is to become established within society, it requires public support. Otherwise tensions are liable to arise, as with the use of nuclear energy for electricity production and the introduction of genetically modified crops. Amongst policy-makers and in the scientific and business communities, lack of support is often attributed primarily to the general public's lack of understanding of the new technology. However, research has shown that the main reasons why the public withholds its support for a technology are mistrust of the companies introducing the technology, lack of confidence in the government as protector of the public interest, and scepticism about the feasibility of reaping the benefits of the technology while also managing the risks.[64-66]

Not surprisingly, little research has yet been conducted into the likely public response to hydrogen-powered road vehicles. After all, such vehicles have so far been trialled only on a very small scale. Nevertheless, the research that has so far been published (including the Amsterdam hydrogen bus project[67]) suggests that the technology is unlikely to be met by significant mistrust.[28,67,68] Although a more sustainable means of fuelling road vehicles may expect a generally positive reception, various studies also indicate that acceptance of hydrogen-powered cars would depend largely on price and performance. The siting of refuelling stations could also be an issue. People living nearby would benefit only marginally, but would be confronted by an unfamiliar risk over which they have no personal control.[69]

If policy-makers and entrepreneurs continue to regard the development of hydrogen technology as an attractive option, the question of public support will need to be considered. In this context, it will not be sufficient to inform people about the benefits, the extra initial cost of which can be offset by subsidies and government investment (probably on a large scale).[3] It will also be necessary to address the risks and to allay any public fears that may exist regarding them. Furthermore, the authorities need to remain alert to the possibility of unforeseen problems.

5.3 The need for transition management

The fourth National Environmental Policy Plan (NMP 4) puts forward several scenarios for transition to a sustainable energy economy.[70] One of the postulated outcomes is the emergence of hydrogen as the pre-eminent energy carrier. A major change of this kind would involve a process of transition. Since publication of the NMP 4, the Interdepartmental Energy Transition Project Directorate has been working on a transition policy. In this context, 'transition' is interpreted as a major change in the way that a social function (such as transport) is fulfilled. With its far-reaching repercussions, the introduction of hydrogen technology would constitute such a transition.

This implies a need for government-supervised transition management.[71] The complexity and extremely long timescale of the changeover also make government supervision desirable.[3] The sustainability of the energy sources used and the way in which the infrastructure is realised will be important themes in this context.

In recent years, several reports have been published on the transition to large-scale hydrogen use.[27,72,73] However, many of these reports focus largely on the technological aspects of the transition process. The Committee believes that it is also essential to consider the public acceptance dimension, if society is to reap the potential benefits of hydrogen technology. Furthermore, consideration for the public health implications must, in the Committee's view, form an integral component of the approach adopted, alongside consideration for the economic implications and for the local and global environmental implications.[71]

Careful, staged transition management can provide a setting in which the public health dimension is naturally afforded appropriate attention during the development and possible introduction of hydrogen technology. Such an approach would also allow for delayed adverse health effects to be detected and tackled wherever possible. The Committee believes that the value of managing the transition in the manner described would not be confined to the prevention or mitigation of adverse health effects.[6] When a new technology is developed and introduced, the application pattern associated with it inevitably 'evolves'. This can yield potential health and welfare benefits: opportunities that may pass unnoticed without diligent monitoring. As far as the Committee can ascertain, such opportunities have yet to be taken into proper account; instead, development of the technology is dominated by the concept of substitution – simply replacing petrol with hydrogen.

The Committee supports the view that new technology should be introduced gradually in the context of a democratic process.[74] It is impossible to predict exactly what the outcome of that process will be. However, the advocated approach would make it possible not only to exercise caution in relation to unforeseen hazards, but also to make the most of any unforeseen opportunities – other forms of mobility – afforded by hydrogen technology.

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A The Committee

B Key information about hydrogen

Annexes

Annex **A**

The Committee

- Professor W.F. Passchier, *chairman*
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- Dr. J.W. Erisman
  Chemist, Biomass, Coal & Environmental Research Unit Manager, Energy Research Centre of the Netherlands, Petten
- Drs. P.J. van den Hazel
  Physician, specialist in environmental medicine, Central Gelderland Social Support Unit, Arnhem
- Professor D. Heederik
  Professor of Health Risk Analysis, Institute for Risk Assessment Sciences, Utrecht University
- Professor R. Leemans
  Professor of Environmental System Analysis, Wageningen University and Research Centre
- Dr. J. Legler
  Toxicologist, Institute for Environmental Studies, VU University Amsterdam
- Dr. J.P. van der Sluijs
  Researcher in science, technology and society, Copernicus Institute for Sustainable Development and Innovation, Utrecht University
- J.W. Dogger, *scientific staff*
  Health Council, The Hague

- Dr. P.W. van Vliet, s*cientific staff*
  Health Council, The Hague

The Health Council and interests

Members of Health Council Committees – which also include the members of the Advisory Council on Health Research (RGO) since 1 February 2008 – are appointed in a personal capacity because of their special expertise in the matters to be addressed. Nonetheless, it is precisely because of this expertise that they may also have interests. This in itself does not necessarily present an obstacle for membership of a Health Council Committee. Transparency regarding possible conflicts of interest is nonetheless important, both for the President and members of a Committee and for the President of the Health Council. On being invited to join a Committee, members are asked to submit a form detailing the functions they hold and any other material and immaterial interests which could be relevant for the Committee's work. It is the responsibility of the President of the Health Council to assess whether the interests indicated constitute grounds for non-appointment. An advisorship will then sometimes make it possible to exploit the expertise of the specialist involved. During the establishment meeting the declarations issued are discussed, so that all members of the Committee are aware of each other's possible interests.

Annex **B**

Key information about hydrogen

This Annex is based on [76].

Table 1 Key information about the element hydrogen (H).

Atomic number	1
Atomic mass	1.007825 g×mol^{-1}
Density	0.0899×10^{-3} g×cm^{-3} at 20 °C
Melting point	-259.2 °C (13.95 K)
Boiling point	-252.8 °C (20.35 K)
Isotopes	1 and 2 neutrons (deuterium and tritium)
Initial ionisation energy	1311 kJ×mol^{-1}
Discovered	in 1671 by Boyle

Hydrogen is the first element in the periodic system. Under normal conditions, it is a colourless, odourless and tasteless gas, formed by diatomic H_2 molecules. The hydrogen atom (H) consists of a single-proton nucleus and a single electron. Hydrogen is a constituent of water and of all organic compounds; it is present everywhere, not only on earth but also throughout the universe.

Applications

Hydrogen's main application at present is ammonium synthesis. It is also used in fuel production, for processes such as hydro-cracking (the breakdown of substances by hydrogen) and sulphur elimination. Large amounts of hydrogen are consumed during the catalytic hydrogenation of unsaturated vegetable oils to make solid fats. Hydrogenation is used in the fabrication of organic products. Finally, hydrogen is used as rocket fuel.

Properties

Some of hydrogen's primary properties are summarised in table 1. Hydrogen is the most easily inflammable of all known substances. It is slightly more soluble in organic solvents (such as ethanol) than in water. Many metals absorb hydrogen. Absorption of hydrogen by steel results in embrittlement.

At room temperature, hydrogen is not particularly reactive unless activated by, for example, an appropriate catalyst. At high temperatures, hydrogen is highly reactive.

Although hydrogen is normally diatomic, its molecules separate into individual atoms at high temperatures. Free hydrogen atoms are highly reactive, even at normal temperatures. They react with the oxides and chlorides of metals such as silver, copper, lead, bismuth and mercury. Hydrogen reacts with a number of metallic and non-metallic elements to form hydrides. Hydrogen atoms can react with oxygen to form not only water, but also hydrogen peroxide (H_2O_2).

Hydrogen reacts with oxygen to form water, but the reaction is very slow at normal temperatures. However, if the reaction is accelerated by a catalyst or an electric spark, it occurs with explosive speed. The range of explosive concentrations is relatively wide compared with other fuels (Figure 4).

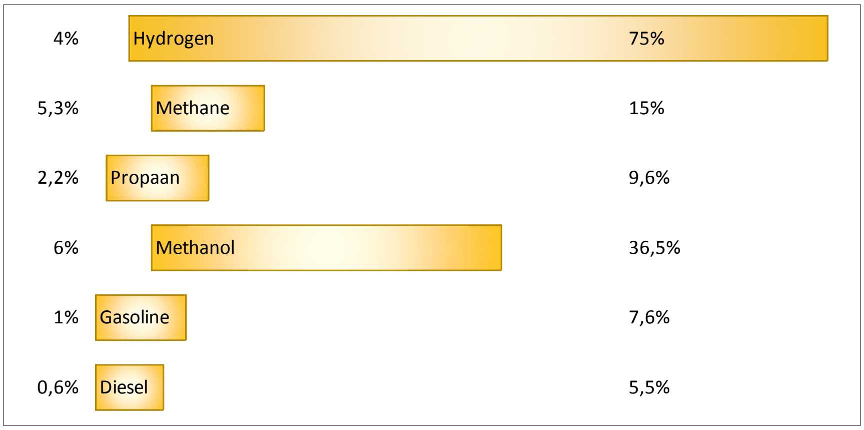

Figure 4 Inflammability ranges of juel-air mixtures under normal temperature and pressure.[77]