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July 1999

New materials for energy conservation and energy transformation

Summary

Working report no. 62

TAB
Office of Technology Assessment
at the German Bundestag

SUMMARY

At the suggestion of the Committee for the Environment, Nature Conservation and Reactor Safety, a study was carried out on the status, prospects, opportunities and risks of the development and use of new materials for energy conservation and transformation. It was decided to focus on high temperature materials for gas turbines, materials for solar cells and superconducting materials. As the manufacturing technologies (available or to be developed) have significant and sometimes even decisive importance, consideration was not limited to the materials to be used.

As a supplement to the preliminary study presented here, an extensive materials volume was prepared, containing more information on the scientific and technological constellations and examining individual materials and applications in greater detail. The materials volume is available on request from TAB.

Development, manufacture and processing of new materials for innovative applications has outstanding importance for many areas of technology and industries. New materials form the basis for advances in virtually all important areas of technology. The future competitiveness of Germany as an industrial location is closely tied to innovations in materials. In addition, the development of new materials and the associated production and processing technologies has considerable ecological impact (reducing pollution, conserving resources etc).

The central role of new materials in the development of innovative technologies and new, marketable products is relatively neglected in public perception. One reason for this is that the user is primarily concerned with the functionality of a new or improved system or product, and the elements which actually determine (the materials used) this duly take second place. Another consideration from industry's point of view is that the income from manufacturing the materials themselves is generally minimal, compared with income from products and systems.

New developments in materials do not just affect areas of technology which are directly concerned with materials. Advances in technologies which are not connected with new materials at first glance depend extensively on the development of new materials. The importance of new materials for applications in classic areas of technology is illustrated by their use in the energy sector. Their cross-sectional nature is particularly clearly demonstrated by the conventional division between functional and structural materials. New structural materials with greater thermal and chemical resistance (particularly structural ceramics

and structural metals) are intended to improve the efficiency and economy of conventional energy technologies, particularly in converting fossil fuels into electrical energy. Special physical characteristics of functional materials are exploited in new conversion technologies (for example, the – photovoltaic – conversion of solar radiation into electrical power) or in reducing losses in energy transmission and use (for example, through the industrial use of superconductivity), and hence saving electrical power.

The goal of the present study is to use three fields of application to analyse the current state of development and special features of the manufacture of materials selected for these.

The present study follows scientific and technological practice in the current debate of using »new materials« to refer to the leading edge of materials research and development. New materials must accordingly differ from existing materials in their physical structure, chemical composition or function. Their development essentially follows one of two paths: modification of the physical structure or chemical composition of conventional materials or new concepts.

As a topic, »New materials for energy conservation and energy conversion« links a number of topics and areas of technology, along with various groups of materials. The present study looks in depth at three selected areas of application for new materials, where some of the areas already have individual applications and some are still in the research stage:

> high temperature materials for gas turbines
> materials for photovoltaics
> superconducting materials for energy applications.

The common element is their shared goal of generating, transporting, storing or using (electrical) power in an efficient, low-cost manner which also spares the environment and conserves nature. A large number of approaches are being followed:

> Improving the efficiency of classic conversion technologies (e.g. improving the efficiency of gas turbines or steam generators through higher temperature or pressure) and hence reducing fuel consumption.
> Improving the economy of technological systems by reducing manufacturing and operating costs, increase their performance and extending their useful life.
> Improving the ecological tolerance by reducing flue gas emissions.

> Developing and improving new conversion technologies for using renewable energy resources.
> Improving the efficiency of electricity transfer and application technologies, and hence reducing losses.
> Developing new technologies which cannot be implemented with existing materials (or not implemented with an adequate prospect of economy).

The current state of knowledge in materials development is increasingly permitting customised production or improvement of materials. Here, the properties of the material no longer dictate its use: instead, the development goals are derived from the desired functions of the systems or products. Based on the definition of a desired technological service, a use profile is elaborated which defines the requirements for the materials used together with the development goal. Customised materials accordingly reflect a substantial qualitative advance in the materials field.

PHOTOVOLTAICS

The use of solar energy for photovoltaic and solar thermal installations is now state-of-the-art. A breakthrough in the energy sector – particularly for photovoltaic generation – has so far been held up by the relatively high manufacturing costs of photovoltaic solar cells and their low level of efficiency together with the complicated techniques needed to integrate them into a system. Photovoltaic use in stand-alone installations is the only case which has proved cost-effective to date. Besides work on improving the solar cell concept based on the »classic« material silicon, there is accordingly a worldwide search for new materials for photovoltaic cells. The search is for materials which will make possible solar cells which are cheap to manufacture, have a high degree of efficiency and long useful life and cause little pollution in manufacture, use and disposal (recycling).

The conclusions of the study can be summarised as follows.

> In the balance sheet for photovoltaic installations, the solar cell is just one component. Other potential sources of cost savings which have not been exploited fully to date are modular production, system technology and integration. From our present point of view we cannot expect that innovations leading to lower specific costs of cells will by themselves offset the cost penalty of photovoltaic systems in the foreseeable future. What is needed is improvements in other areas, which may even be attainable with less investment.

> For the solar cells themselves, other important factors besides the photovoltaic material itself are the cell design, the production technologies used and possibly the substrate or superstrate material. Innovations in solar cells are accordingly not restricted to introducing new materials or modifying existing ones. New cell concepts, new or modified manufacturing processes or the use of new »adjuvants« also make possible improvements in efficiency and/or cost savings.
> Currently (and for the next 10 years at least), crystalline Si will continue to be the most important material in solar cell production, as it has many advantages and also benefits from the high level of technology in microelectronics. In addition thin-film technologies with amorphous Si are already on the market, and selected new thin-film technologies based on CdTe, CIS and Si will be introduced shortly.
> Crystalline Si solar cells still have substantial potential for improvement in terms of both efficiency and manufacturing costs. New manufacturing technologies in wafer production aim at reducing material losses and production times, and major potential for rationalisation has been demonstrated in subsequent production of solar modules. New cell designs (so-called high-efficiency cells) promises increases in efficiency. However, studies are still in progress on how far these are suitable for series production and what efficiency is needed to justify additional cost of production in terms of higher energy yield.
> In the longer term the large material use of crystalline silicon and the elaborate Si wafer technology could mean that the future of solar cell technologies will lie with thin-film technologies with large-area deposition. However, extensive development resources are needed to make these thin-film cells more cost-effective than crystalline Si cells.
> The various competing thin-film concepts are in very different stages of development. Currently, it is not possible to say that one technology has a clear technical and economic lead over the others for the future. In addition to technical and economic considerations, there are also questions of availability of resources and the toxicity of materials used (and hence their acceptance) in what is currently a rather »green« market.
> In the foreseeable future R&D should be continued on a broad front, in order not to lose an important option. There is still substantial need for R&D in a number of areas:
  - The »established« technologies using crystalline silicon solar cells need to be further developed so that solar cells show greater efficiency, need less material and can be manufactured more cheaply.
  - The innovative thin-film technologies also naturally need to meet these three requirements. First, however, all of them (except for amorphous Si) need to demonstrate homogeneous production over a large area.

In principle, new solar cell concepts and materials cannot generally be ruled out for the future, but they are not currently in sight. Many innovations announced with great excitement in recent years have been abandoned before leaving the laboratory.

GASTURBINES

Stationary gas turbines have become significantly more important in electricity generation worldwide in recent years, not least due to the trend towards liberalisation of the energy and gas markets. Today, they are a standard technology for electricity generation. Gas turbines are very flexible in terms of low cost, range of fuels and rapid availability, and are currently on a rising trend. Even if there are limits to improving their efficiency, further progress towards the thermodynamic limits is still possible. A further increase in efficiency is desirable because more efficient utilisation of fuel conserves natural resources and reduces the release of pollution into the environment.

In achieving an increase in efficiency new and improved materials have a major role to play. The focus is on four classes of materials: metallic materials (superalloys and intermetallics), ceramic materials (structural ceramics), composite materials with a ceramic matrix (carbon fibre reinforced carbon) and surface coatings (heat insulation layers). New high-temperature materials are expected to show characteristics which are at least as good as and probably significantly better than conventional materials, attainable at low cost if at all possible. A striking feature is the large number of individual questions currently being studied in new high-temperature materials. Major improvements have been achieved in individual application and production characteristics (where material developments in gas turbine construction have so far profited mainly from developments in aviation turbine construction), but superiority over the entire characteristics profile has yet to be demonstrated.

With oriented or single-crystal superalloys surface temperatures of c. 1,000°C have already been achieved. An increase in surface temperature to c. 1,100°C will be attainable with metallic components such as improved or oxide-dispersion-strengthened (ODS) superalloys. A significant increase in surface temperatures to c. 1,400°C will require the development of ceramic structural materials. A further increase in temperature will mean a switch towards composites (e.g. carbon fibre reinforced carbon). Allowing for a time dimension in development, this means:

> In the relatively short term and with a high probability of success, we can expect further improvement of Ni-based superalloys. Processes for making oriented or single crystal materials give components favourable characteristics in the direction of main stress. Stabilising additives, e.g. of oxides, further improve their high-temperature performance. In the case of ODS superalloys production is significantly more expensive, as these are not suitable e.g. for cheaper casting processes. The boundaries for superalloy use are determined by their melting point and specific damage scenarios, such as crack formation along crystal boundaries in the single-crystal case.
> In the medium term we can look for the use of fully-ceramic turbine blades. Ceramic materials can largely do without cooling and heat insulation coatings. There is also medium-term potential for industrial use of intermetallics, which are distinguished by their resistance to heat and low specific weight. Both classes of materials suffer from the disadvantage of brittleness in use and manufacture. The tendency of ceramic materials to fracture can be reduced, but not fundamentally eliminated. For this reason it should be assumed that their advantages will only be fully apparent in ceramic-specific component designs.
> In the longer term there is potential for the use of turbine components from composites, such as carbon fibre reinforced carbon. The appeal of this class of materials lies in the ability to manufacture »custom-built« materials. Their use is limited by brittleness and the sensitivity of the fibres to oxidation. As a result, hopes are set on developing new surface protection systems.

Surface coatings applied as heat insulation play a supplementary role in almost every high-temperature material, mostly compensating for corrosive conditions and accordingly with a stabilising function. This makes it possible to raise the temperature in use of individual components by up to 100°C. Problems affecting practical use such as stability and adhesion of coatings, for example in multilayer systems, seem to be soluble in the medium term.

For the high-temperature materials for gas turbines under consideration here these relatively high expectations for new materials are offset by extensive need for R&D, e.g. in the following areas:

> improving our theoretical understanding of material structure (e.g. carbon fibre reinforced carbon), of reinforcing and hardening mechanisms (e.g. ODS superalloys, concepts of 3-dimension reinforcement for CFRC) and material behaviour at high temperatures (interactions of material components, damage scenarios etc),
> optimising the material structure (e.g. limiting the variation in rigidity and optimising the sintering process for ceramics, the relationship between set pro-

duction parameters and the resulting component characteristics for CFRCs),
> improving current manufacturing processes (e.g. for oriented superalloys, application of heat insulation layers), developing new, low-cost production processes (e.g. for series production of intermetallics) and
> developing suitable test procedures for quality assurance in production, particularly in the high-temperature area (for reproducibility of material characteristics in the manufacturing process, as there are still no specific characteristic values for materials and components etc).

SUPERCONDUCTORS

Superconductors can (theoretically) be used at all levels of production in the electricity industry (conversion, transport and distribution). For some time, energy technology has been seen as a major area of application for superconducting materials. Besides improvements in known technological systems (superconducting generators, transformers, cable) where low electrical losses with superconductors make possible achievement of higher efficiency and the high power density means reduced volume and weight, there are also new concepts under discussion (e.g. fault current limiters using superconducting materials and the use of superconducting magnetic energy storage). However, complex technologies are requires, particularly for cooling the superconductors, and the energy consumed by these reduces or outweighs the advantages of the low-loss conductors. In addition, production of wires is considerably more difficult and elaborate, compared with conventional copper wires, and the systems themselves are frequently more complicated, so that major efforts are needed to achieve the same reliability and availability as with the conventional alternatives now available. This in turn leads to higher system costs.

The discovering of high-temperature superconducting materials in the mid-Eighties gave new life to old expectations for superconducting technology in the electricity industry. The new materials and their energy sector applications do not involve any fundamental change in the underlying physical and technical principles or the environment in which they are used. The use of a »higher« temperature range for cooling could, however, mean that simpler and cheaper cooling systems can be used, and the expense on thermal insulation could also be reduced. On the other hand, the characteristics of the new materials had first to be investigated and understood, and processes for manufacturing conductors suitable for the various applications had to be developed.

For the »classic« high-temperature superconductors, we need to develop new concepts and manufacturing processes and improve existing ones for producing conductors which are suitable for energy industry applications.

The »controllability« of a material is a fundamental factor in practical use. In the case of high-temperature superconductors, numerous advances have been made in the past ten years, and our understanding of the main materials is now adequate. There is, however, no sign of an accepted physical theory of high-temperature superconductivity, despite widespread efforts and numerous original and stimulating ideas. More fundamental research seems required here.

In recent years, numerous processes have been developed for producing conductors using high-temperature superconducting materials. Each of these has specific strengths and weaknesses. For the implementation of the processes in industrial-scale manufacture the key principle that seems to be emerging (for both physical-technological and economic reasons) is the need to keep these processes as flexible and simple as possible, and only use as many process stages as are needed to reach the required parameters.

Among the high-temperature superconducting currently being extensively researched, YBCO shows significantly higher current density at 77K compared to the Bi materials. Due to its structural characteristics, the material cannot be used in the form of rolled tapes or wires. Coating procedures for conductor manufacture were only successful over lengths of a few centimetres. Currently, deposition of thick films of YBCO on flexible metal substrates seems particularly promising, with subsequent processing using various technological approaches. However, several years of development work will be needed before longer conductors can be produced in this way. Bi-based conductors (BSCCO compounds) permit simpler manufacture of wires and tapes. However, they lose their superconductivity at 77K with even medium-strength magnetic fields which occur in many energy industry applications as an integral part of the functional principle. In the range 20-30K, however, PIT-manufactured Bi conductors show good technical data. It is hoped that new technologies will make it possible to maintain superconductivity at »higher« temperatures and/or with stronger magnetic fields. Very promising results have already been achieved with short wires, but it remains to be seen whether these techniques are practical and economical for longer conductors.

Although over 100 compounds which can be described as high-temperature superconductors are already known, the search for further materials should be continued. The emphasis should be less on materials with higher critical temperatures: for most energy industry applications it will be more important to find superconductors which:

> are relatively simple to manufacture in the form required for the application (long wires in particular),
> maintain superconductivity even in strong magnetic fields, at higher temperatures (at least liquid nitrogen) and possibly under moderate mechanical stress,
> have few problems in terms of availability of resources, toxicity and disposal.

The empirical search for new materials will continue to play the central role here, although in future a suitable theoretical explanation of the mechanism of high-temperature superconductivity should be found.

Superconducting components for applications in the electrical industry permit (irrespective at this point of the superconductor actually used) either entirely new technological systems or will replace conventional systems because of their more favourable technological and economic parameters. The decisive breakthrough for energy industry HTS applications at 77K will only be possible if the HTS can be manufactured with suitable technical configurations. It is not clear what the electrical parameters and costs will be for manufacturing suitable technical HTS on an industrial scale. It is, however, clear that there will be no single »all-purpose« superconductor for energy industry use: instead, technical and economic optimisation will lead to a wide range of concepts in the selection of the superconducting material and also the conductor configuration.

In the light of our present knowledge, the possible uses for the individual applications (assuming availability of suitable and »affordable« conductors) can be summarised as follows.

> For rotary machines (large motors and generators) improving the efficiency is comparatively unimportant. Such systems already show efficiencies of 98% and the use of superconducting materials would add another 1–1.5%. Particularly with the large motors, large numbers of which are in operation in Germany, this can be relevant at the macroeconomic level. However, there is considerably greater potential for improvement in efficiency in the systems attached to the electrical machinery, such as steam turbines (with generators) and pumps and blowers (with motors). Superconducting generators are only more economical than conventional systems in designs of several hundred MVA, and demand for generators of this size is relatively small in view of the current trend in power stations. It is unclear how far the market will actually respond to other properties, such as smaller size, reduced weight and improved operating

characteristics. In the longer term there should be prospects for superconducting generators in particular if construction of major (nuclear?) power stations should be resumed.

> The largely resistance-free transmission of power in superconducting cables is seen by the public as the most appealing use of superconductivity. Numerous projects using HTS materials are currently in progress. The short-term prospect for most of this work is on the use of such cables to carry electricity in metropolitan areas (particularly for retrofitting existing systems). In the longer term their use is envisaged in a global electricity grid, still to be designed and with discussion needed above all of its aspects above and beyond simply functionality, in which high-tension DC power transmission is likely to play an extensive role.
> Superconducting transformers are another case where improved efficiency is of less importance to operators (although by no means negligible) than their improved operating properties, the advantages of eliminating oil as an insulator and the reduction in specific weight and volume, which could create markets particularly in retrofitting for densely-populated areas. Currently, a number of prototypes are in field testing.
> Larger SMES installations to balance daily loads are not economical in current terms. Depending on the electricity industry structure in which the storage technology is integrated, it could also involve ecological disadvantages. In the long term – given major changes in the organisational structure of the electricity industry and the makeup of the generating capacity – there may be increased demand for storage technologies. However, the present state of the art does not indicate any clear technical or economic superiority for SMES compared with other, conventional storage technologies. We do not know of any plans to develop large SMES.
> One conceivable alternative to the small SMES is flywheel storage with superconducting bearings. Usable in principle for the same applications as small SMES, further development will have to decide which is the more attractive technology in economic and operational terms.
> Currently, the only superconducting technology attracting serious interest is the superconducting fault current limiter. This is expected primarily to lead to improved voltage quality and lower grid impact. It is, however, still unclear which functional principle has good chances of implementation or what concept it will actually be implemented in. Further development work is required here.

Given the complex energy industry systems and the long development and testing cycles together with the currently uncertain prospects for commercial success for superconducting systems, it seems unlikely that purely industrial R&D will be conducted on any scale in this area. In competition with conventional systems, tested and improved over a long period, new technologies are always at a disadvantage in demonstrating their functionality, reliability and availability. Apart from fundamental research, government support would be essential, particularly for pilot projects and demonstration installations, if these technologies are to be developed further and tried out.

For the evaluation of the long-term prospects of superconducting energy technologies it will not be sufficient to compare these with their conventional alternatives. It would be interesting to design a »superconductor-based« electricity supply system and put this into a macroeconomic framework for comparison with the current systems and systems evolving in the new environments.

At present, ecological evaluation of the use of new materials in energy technology is only possible in rudimentary form. On the one hand, for example, the use of high-temperature materials in gas turbines promise an increase in efficiency, with resulting reduced energy consumption and pollution. The desired – and achieved – high resistance of these materials to thermal and chemical influences could, however, reduce their recycling capability. Materials for solar cells are a contribution to electricity generation which is pollution-free in operation, but their manufacture requires substantial energy input. .Generally, it can be said that (with a few exceptions) we lack the research results and assembled information to reach a satisfactory evaluation of the ecological consequences of the use of new materials. Many companies (particularly SMEs) lack the data on conventional and (particularly) new materials to draw up ecological balance sheets, and frequently also lack the personnel. It would be desirable to pay greater attention in future R&D activities to aspects of ecological evaluation in materials development.

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