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WORKSHOP ON COATINGS NEEDS IN THE AUTO INDUSTRY

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EXECUTIVE SUMMARY

New lightweight materials continue to be of great interest to the automotive industry. Compared to 20 years ago, the average vehicle weight has been reduced by almost a fourth, and fuel economy has nearly doubled. While continued improvements are both desirable and possible, materials choices are narrowing and the manufacturing methods needed to produce advanced materials systems are much more costly. The incentives remain high, however; particularly in view of large payoffs associated with minimizing structural weight in electric and hybrid-type vehicles. One generic solution is to develop coatings that will enable the use of lower cost materials.

The materials for lightweight vehicles program, which has been initiated through the Office of Transportation Materials, U.S. Department of Energy, is considering coatings as complements to a variety of advanced materials options. The first step is to identify where coatings can make a significant contribution, and the second is to focus on research areas that would have the greatest short-term impact.

A workshop on coatings needs in the auto industry was held in Detroit, Michigan on October 27 and 28, 1992 with the objective of identifying research needs where coatings could enhance the use of energy efficient lightweight materials for automotive applications. Research staff from the three main American auto manufacturers, Chrysler, Ford, and General Motors, participated

in chairing the sessions and directing the discussions. Four generic areas had previously been identified through response to questionnaires and interactive discussions with both auto manufacturers and industry suppliers. These were: Wear Coatings, Hard Protective Coatings for Plastics, Solar Control Coatings, and Process Manufacturing Issues. Paints and paint application processes were specifically excluded since at least one other workshop on these topics had been held.

After identifying and ranking the top research needs, the development of coatings and coating technologies for lightweight metals and metal matrix composites emerged as the number one priority. This need underscores the interest in making better use of existing lightweight metals, e.g. magnesium, aluminum, and their alloys. New or expanded applications for lightweight metal matrix composites could emerge if suitable protective coatings can be developed.

Coatings to protect plastics and reinforced plastic composites were also identified as a major area of importance. At the top of the list is protection from automotive liquids and gases, e.g. alcohol containing gasolines, antifreeze, brake fluid, etc. Coatings that will improve mar resistance, resist UV degradation, or eliminate degradation due to moisture absorption are also needed.

Process technology issues are of particular significance because of the high volume manufacturing character of the auto industry which underscores the need to coat large numbers of complex shaped components reliably, reproducibly, and at reasonable cost. Accordingly, manufacturability issues associated with coating light metals, e.g. aluminum, magnesium, and metal matrix composites with wear and corrosion resistant materials, were identified as a high priority research need.

Recyclability is another major issue that is inherent in all chemical and materials related processes. Coatings could affect the recyclability of the parent component. For example, if the coating is mixed into the recycle stream, it might contaminate the base material.

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INTRODUCTION

Two important missions of the Office of Transportation Materials - a Division of Conservation and Renewable Energy, U.S. Department of Energy (DOE) - are to improve the energy efficiency of automotive vehicles while helping U.S. industry improve global competitiveness. To this end, a cooperative R&D initiative is being organized with the objective of aiding in the development of new and improved lightweight materials and/or process technologies through the formation of partnerships between the U.S. automotive industry and the DOE national laboratories.

As a part of this initiative, a workshop on coatings was held in Southfield, Michigan on October 27-28, 1992. Participants are identified in the distribution list by an asterisk (*) next to their name. The objective of this workshop was to identify generic research needs where coatings could enhance the use of energy efficient lightweight materials in automotive applications. The agenda, which was based on industry response to a prior questionnaire, focused on four categories: Wear Coatings, Hard Protective Coatings for Plastics, Solar Control Coatings, and Process Manufacturing Issues. **Paints and paint application processes were not included as part of the scope of this workshop since these topics were covered in another DOE sponsored meeting.**

Dr. Sid Diamond from the Office of Transportation Materials keynoted the meeting with an overview of DOE's Lightweight Materials Development Program. Principal materials applications for personal vehicular transport are shown in

Figure 1, and can be classified into three areas: (1) propulsion system materials, (2) structural vehicular materials, and (3) alternative fuel system materials. Required attributes of all prospective materials include

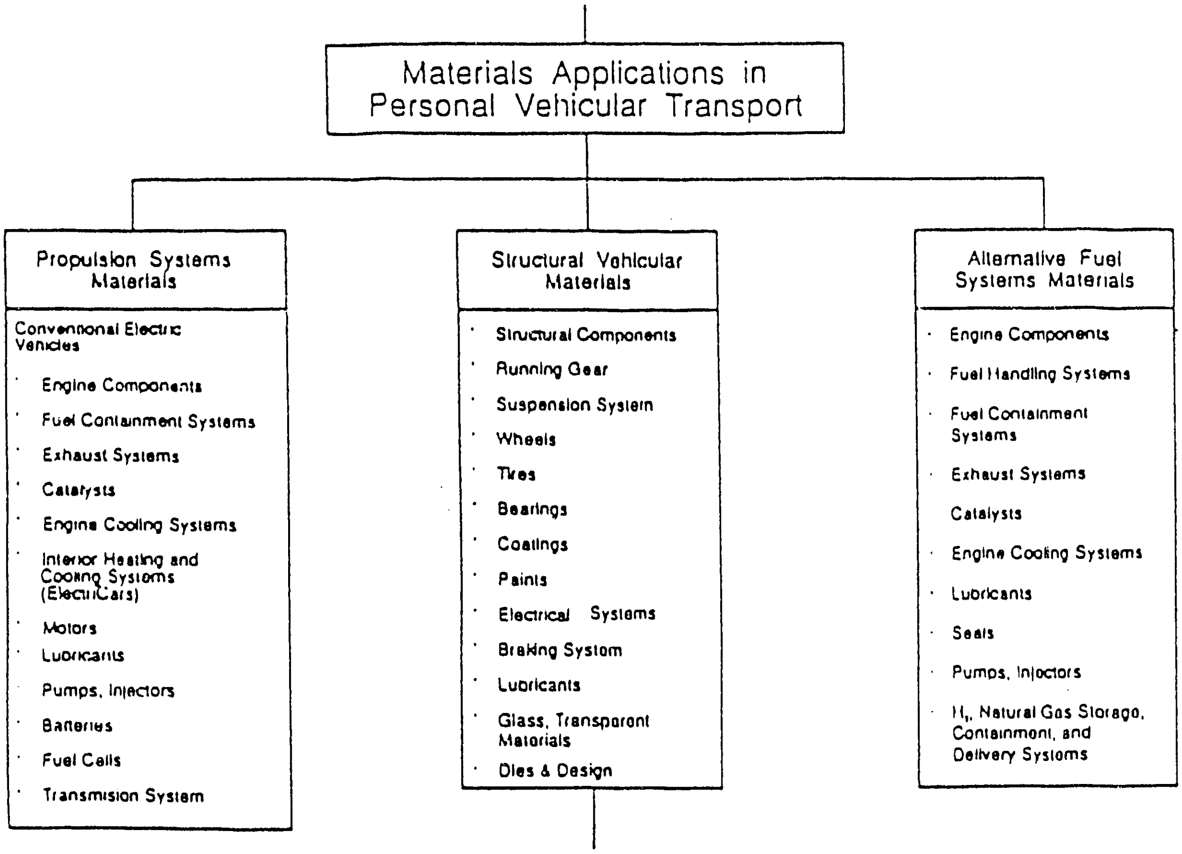

Figure 1. Materials Applications; Re: Preliminary Program Plan, DOE Office of Transportation Materials.

environmental compatibility, recyclability, and manufacturability by processes that comply with safety and health regulations. The program will place emphasis on focused goals and timely responses to industry needs, but the research must also be relevant and provide functional output, e.g. testing parts and components in actual applications. Scientists at the DOE laboratories are expected to contribute by conducting fundamental investigations of structures, properties, and processes. The program will be designed to address economic, social, and national imperatives. An important goal is to help the American auto industry improve global competitiveness.

A summary discussion for each of the four main sessions is provided below, along with a list of prioritized research needs identified during workshop discussions.

WEAR COATINGS

The first session on Wear Coatings was co-chaired by Pierre Willermet of the Ford Motor Company and Dexter Snyder of General Motors Corporation. Professor Ramalingam from the University of Minnesota gave an introductory technology overview on the science of tribology in which the basic principles of friction and wear were reviewed and the role of lubricants discussed. Many important issues, associated with the interaction of surfaces in relative motion, involve hostile environments; thus, simple solutions are uncommon and usually inappropriate. A recommended methodology is to engineer surfaces that will improve surface mechanical properties, reduce failure modes, and extend component life. This approach has been used successfully to develop coatings for high-speed cutting tools.

The basic wear processes were classified into five major categories: abrasive, adhesive, chemical, surface fatigue, and impact/erosive. Some automotive applications have closed tribo-systems where direct access to the component is not possible. Failure cannot be easily monitored under these situations, and the cost of failure is a major concern. If a coating fails, the operative tribo mechanism rapidly changes from two-body to three-body wear because of the debris. The result is often accelerated deterioration and failure of the underlying component. Potential failure mechanisms for several typical components in automotive applications are listed in Table I.

Table I. Failure Mechanisms for Several Automotive Components.
Re: S. Ramalingam, University of Minnesota, after T.E. Quinn

Key: ● Yes; ○ No; Some times; Possibly

		Plain bearings	Rolling bearings	Gears	Brakes / friction surfaces	Seals	Rail and wheel systems	Cams and tappets	Valves and valve seats	Pistons and cylinders	Dry bearings
is sliding wear involved in failures ?	Severe wear	No	Yes	No	Some times	Some times	Yes	Some times	Some times	No	Yes
	Mild wear	No	Yes	Yes	No	Yes	No	Some times	Yes	Some times	No
is fatigue involved in failures ?	Contact fatigue	No	Possibly	No	Yes	Possibly	No	No	Yes	Yes	No
	Fretting fatigue	No	No	No	No	No	No	No	No	No	Possibly
	Thermal fatigue	Possibly	No	No	No	No	No	Yes	No	No	No
is action of particles involved in failures ?	Abrasive particles	Yes	No	No	No	Yes	No	Possibly	No	No	Yes
	Impacting particles	No	No	No	No	No	No	No	No	No	Possibly

L290812 after T. E. Quinn

NSF Meeting May 15 1990 · S. Ramalingam University of Minnesota

One recommended approach to improving surface mechanical properties is to carefully evaluate performance requirements, choose a better material, and then select an economic coating process. An example of identifying tribological requirements and choosing a functional materials system for piston rings is illustrated in Figures 2a and 2b, respectively.

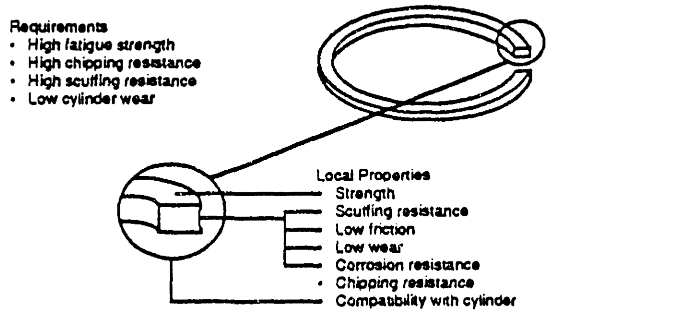

Figure 2a. Tribological Requirements for Piston Rings
Re: S. Ramalingam, University of Minnesota, after Steffens

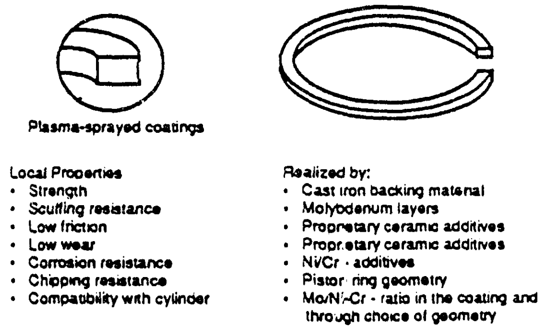

Figure 2b. Potential Materials Systems for Piston Rings

Several thin-film deposition technologies that have been used successfully to deposit tribological quality coatings were reviewed and their process attributes discussed. These included chemical vapor deposition (CVD), plasma assisted chemical vapor deposition (PACVD), physical vapor deposition (PVD), ion plating, and ion beam assisted deposition (IBAD). Factors to consider in selecting a coating process include adherence, intrinsic stress, surface preparation, deposition temperature, and potential changes in physical properties. A good understanding of how deposition processes influence coating properties is essential if wear performance is to be optimized.

Following the overview, Dexter Snyder and Pierre Willermet conducted discussions directed towards identifying research needs. One important topic of discussion involved the use of expert systems and models for intelligently selecting coating materials for a specific application. The development of models to predict tribo-performance is not an easy task. Expanded use of "Ashby" wear maps was suggested by Professor Rigney (Ohio State University) as a good starting point. However, it may be difficult to include some relevant properties like coefficient friction, or to account for lubricant chemistry, in models of this type. It was suggested that the industry could benefit by sharing information about the most common failure modes. Data of this kind could aid in the development of appropriate models, as well as help focus research on the more serious problems.

Another subject of importance is the relationship between bench testing and engine performance. Engine testing is a very expensive process; thus, inexpensive screening tests would be valuable. However, if bench testing is to gain greater acceptance, careful test protocols must be developed. Better methods for correlating failure modes will also have to be identified before design engineers will gain faith in using the results. It will be necessary to understand how materials properties and sample geometries influence the tests and how the results compare to actual engine conditions. Computer modeling of tribo-interactions in engines could be an important research area, but better sensors to measure interface wear in critical engine components need to be developed.

Currently, wear coatings are applied as thin hard films onto hardened, usually ferrous base, components. The benefits of two-stage or functionally graded coating processes where the coating is graded from an initially thick layer to a thin overlayer has not yet been explored in great depth. Models should be developed to help understand how to best utilize graded and multilayer concepts. It was noted that little, if any, work has been done on the application of hard wear coatings to already carbonized or nitride surfaces, and very little work has been done on the application of wear coatings to lightweight materials such as aluminum, magnesium, or metal matrix composites. Professor Rigney noted that research in the USSR is currently studying the use of electromagnetic fields to disperse Pb, on a fine scale, in aluminum alloys in order to enhance surface lubricity.

An important concern associated with increased use of coatings will be the effect that they have on recyclability of the parent component. Some coatings may contaminate the base material and, thereby, prevent recycle back into the process stream. These issues need to be investigated along with methods for coating removal, e.g. laser processing. The impact of recyclability is rapidly becoming a consideration in the initial component design and materials selection phase of new components.

The principal research needs identified for wear coatings are listed below. A supplemental list was constructed by Dexter Snyder who participated in a related workshop conducted by the National Renewable Energy Lab (NREL). These research topics were included for completeness and the asterisks (*) indicate those areas identified as common issues in both workshops.

	Composite Rating (1-5)
• Develop coatings and coating technologies for magnesium, aluminum, and lightweight metal matrix composites.	4.26
* • Study compatibility of prospective coating materials with methanol, and other alternative fuels.	2.41
* • Develop coatings that will extend life of aluminum stamping dies and reduce scratches.	3.38
* • Develop coatings that will enhance the use of inexpensive dies for use in short production runs, e.g., injection molding of thermoplastics.	3.93
* • Develop wear resistant coatings for continuously variable transmissions.	2.67
• Study the effects of coatings on recyclability and develop appropriate processing methods (e.g., laser surface processing).	3.23
* • Develop solid lubricants and coatings, incorporating solid lubricants for operation under conditions where marginal lubrication is available.	3.19
• Develop better understanding of erosion and wear resistant coating requirements for new air compressor designs, including compatibility with new coolant systems.	2.62
• Develop an expert systems methodology for selecting automotive coatings and choosing manufacturing processes.	3.38
• Develop test protocols for evaluating coating systems.	3.54
• Establish correlation coefficients between engine and bench scale tests to assess coating performance.	3.77
• Develop generic understanding of how to optimize and apply multilayer coating systems.	3.37
• Develop surface engineering methodologies for multilayered structures.	3.26
• Develop computer modeling capability for predicting tribo-interactions in engines.	2.84

• Develop measurement probes and surface diagnostic techniques to study interface wear.	3.21
• Develop probes and diagnostic techniques to measure surface temperatures of tribological interfaces.	2.95
• Develop better understanding of performance characteristics and materials limitations of thin sputtered overlays in engine bearings.	2.68
• Study the benefits of laser surface processing of aluminum, aluminum alloys, and metal matrix composites.	2.84

ISSUES IDENTIFIED IN PRIOR DOE/NREL WORKSHOP

• Coatings for lightweight P/T, accessory MTLS.	3.00
• High stress areas - injector tips.	3.06
• Anti-deposit combustion chamber coatings.	3.00
• Gear efficiency and life (heavy-duty).	2.87
• Database/design software.	2.87
• Emissions.	3.44
• Extended tool bit life.	3.56

HARD COATINGS FOR PLASTICS

Strong, tough, and heat-resistant engineering plastics have the potential to increase power and torque per unit of displacement, reduce noise, and decrease weight. Underhood applications include components such as air intake manifolds, valve covers, and timing chain covers. Other uses for coated plastics can be found in electrical systems, cooling systems, fuel systems, and for components that reduce noise or insulate from heat. Lightweight plastics are already being used extensively for interior and exterior trim and for bumpers. Mar and scratch resistant coatings are important for these applications.

This session was co-chaired by Gilbert Chapman of the Chrysler Corporation and Ron Michalak of General Motors Truck and Bus Engineering Operation. The technology overview was provided by Ed Courtright of the Pacific Northwest Laboratory (PNL).

The fundamental issues associated with application of hard coatings, e.g. ceramics, to plastics include the large mismatch in elastic modulus and thermal expansion, as well as the need to manage stress and improve adhesion. Better understanding of the processes that cause surface damage, e.g., scratching, marring, and chipping, are also needed. All plastics have comparatively low thermal conductivities which, for some applications, creates the need for coatings that are capable of dissipating heat.

Many of the new materials choices for environmentally durable hard coatings will likely be ceramic compounds which have elastic moduli on the order of ten times greater, and coefficient of thermal expansions that are ten times less, than plastics. These differences create serious stress management problems. Because of their lower coefficient of thermal expansion, hard protective ceramic coatings will be subjected to tensile stress loading if the application temperature is higher than the coating temperature. Ceramic coatings can typically only survive about 0.1% strain in tension, and are subject to failure when temperatures increase as little as 20°- 40°C above the original coating temperature.

Because of this wide disparity in properties between ceramic coatings and plastics, the introduction of functionally graded interfaces may be a necessity. Two relatively new processes that seem particularly well suited to the application of functionally graded compositions on plastics are: biomimetic deposition or plasma assisted deposition of amorphous-like diamond. Biomimetic deposition imitates the main features found in nature's biomineralization processes that form organic interfaces from functional groups on the substrate surface. This process, which is currently being studied at PNL, is capable of depositing coatings from aqueous solutions at low temperatures, and could easily be applied to large surfaces and complex shapes.

Amorphous diamond-like coatings, e.g. a-C:H, are compositionally similar to many engineering polymers. A schematic relationship between diamond-like coatings and plastics, developed by Professor J.D. Angus at Case Western Reserve, is shown in Figure 3.

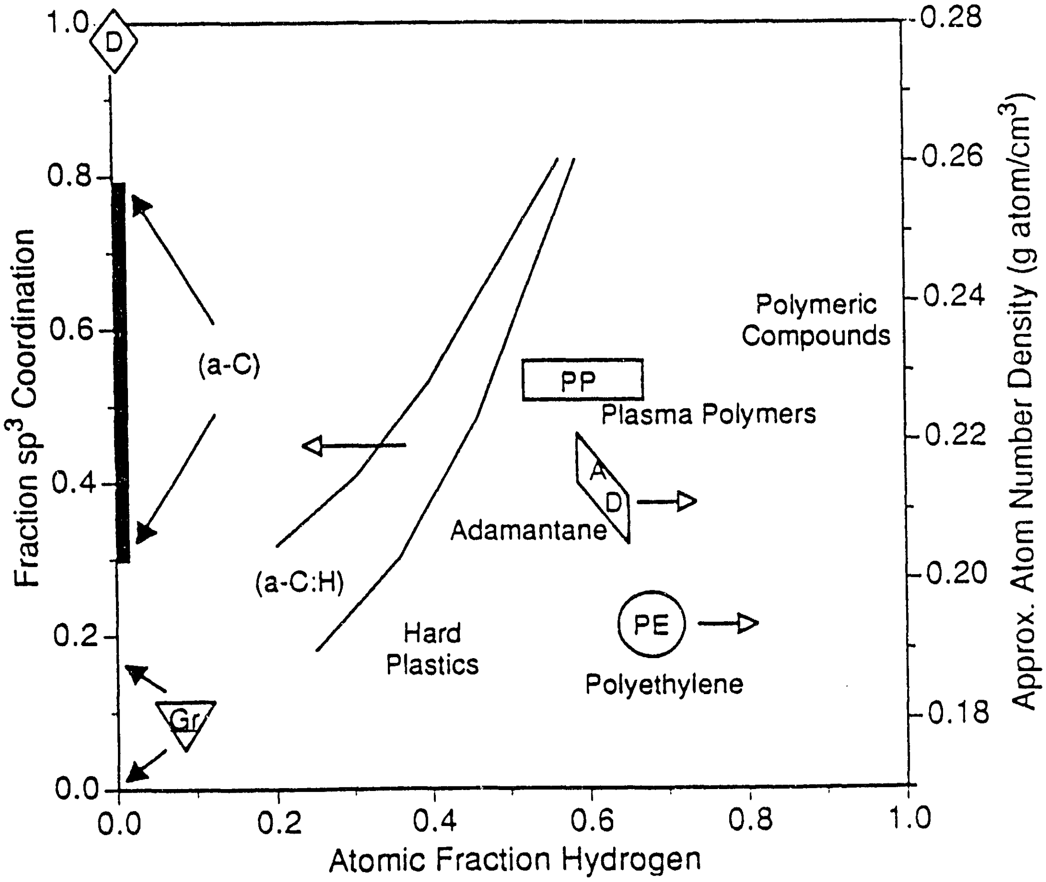

Figure 3. Schematic Relationships Between Diamond-Like Coatings and Plastics. Re: J.C. Angus, Science, Vol. 24, (1988), p. 913; Diamond & Related Materials, I (1991), p. 61.

While the two ordinate scales are not exactly equivalent, this figure provides an interesting perspective. For example, certain functional groups, such as adamantine, provide the embryonic nuclei from which sp^3 diamond-like coordination can be derived. Thus, it should be possible to functionally grade properties from a soft plastic base material - to a harder plastic intermediate layer - to a protective diamond-like outer surface by adjusting composition and bonding relationships. Amorphous a-C:H films exhibit excellent chemical resistance, similar to that of diamond, and hardness in the range of 1500-3000 kg/mm^2, which are about the same as covalently bonded ceramics. As sp^3 bonding increases, visible light transmission improves dramatically. This is an important criterion for coatings that are used to protect plastic automotive glazings.

Discussions leading to the identification of research needs were led by Ron Michalak of General Motors and Gil Chapman of Chrysler. They emphasized that the major use of plastics is currently for interior and exterior panels and trim where cosmetic appearance is important. Decorative coatings are typically applied, but these coatings must also be mar and scratch resistant. Current trends are in the direction of lacquers to thermosets, one-component to two-component systems, and solvent-base to water-base coating processes because of environmental reasons. The development of economically attractive, yet environmentally sound, coating processes are important industry goals.

Currently, all headlamp lenses are made from polycarbonates. Component life could be improved by the application of clear, hard, erosion resistant coatings, e.g., a-C:H. Work at Oak Ridge has recently shown that ion implantation can be used to effectively harden plastic substrates, and a large-scale plasma source ion implantation capability is under development at the Los Alamos National Laboratory. All coatings used to protect soft plastics need to exhibit good chip, mar, and scratch resistance, but coatings that could improve impact damage would be of even greater interest. There is also a large potential market for hard coatings that will improve total component performance, and thereby allow the use of cheaper plastic substrates to replace high-cost polymers.

The issue of recyclability is particularly important for plastics. The development of chemical or physical recycling methods may deserve consideration as a research need. Coatings could prevent the use of scrap as recycle in other plastic components, or may cause problems associated with disposal.

The research needs identified in this workshop for the application of hard coatings on plastics were as follows:

	Composite Rating (1-5)
• Develop coatings to enhance battery efficiency and performance.	2.73
• Develop high emittance or conductive coatings that will help reduce heat in plastic components.	3.35
• Develop coatings to protect plastics from automotive liquids and gasses, e.g., alcohol containing gasolines, antifreeze, brake and transmission fluids.	3.96
• Study ion implantation of plastics with emphasis on economical processing approaches e.g., plasma source ion implantation.	3.33
• Develop diamond-like coatings with graded interfaces to match a variety of polymer compositions.	2.81
• Develop coatings that improve abrasion and enhance environmental protection of plastics e.g., diamond-like/a-C:H.	3.81
• Develop coating to enhance the manufacturability and performance of beads, fibers, and fillers in reinforced plastics.	3.54

- Develop coatings that will enhance impact resistance in plastic components. 3.73
- Study coating techniques that will improve mar resistance, UV resistance, and moisture resistance of plastic materials. 3.92
- Develop suitable wear resistant coatings for polycarbonate head lamps with good light transmission. 2.92
- Develop standardized test methods to help improve the quality of coated plastic. 3.38
- Develop an expert system methodology for use in selecting optimized coatings and processes for plastic components. 3.62

SOLAR CONTROL COATINGS

This session was co-chaired by John Bomback of the Ford Motor Company and Ken Dean of General Motors, and the overview talk was given by Mike Rubin of Lawrence Berkeley Lab. Current trends in automotive design, motivated by both aesthetics and the desire to improve aerodynamics, are towards larger glass areas and steeply sloped windows. During the last decade, the average glazed area per vehicle has increased by almost 50%. Steeper slopes and larger glass areas both increase the solar heat gain in vehicles. This results in greater use of air conditioners and focuses attention on thermal load management. Significant gas savings can be realized simply by reducing the power requirements of air conditioners.

The ideal solar control coating transmits most of the visible wavelengths of the solar spectrum, while reflecting the ultraviolet and infrared, see Figure 4. In addition to reducing solar heat gain, the reflection of ultraviolet wavelengths is desirable because they can damage interior plastics. Current National Standard Safety Codes require 70% visible transmission at normal incidence for the windshield and front side lights, while European codes require 75% transmission. In the future, we may be forced to adopt the more stringent European standards for competitive reasons.

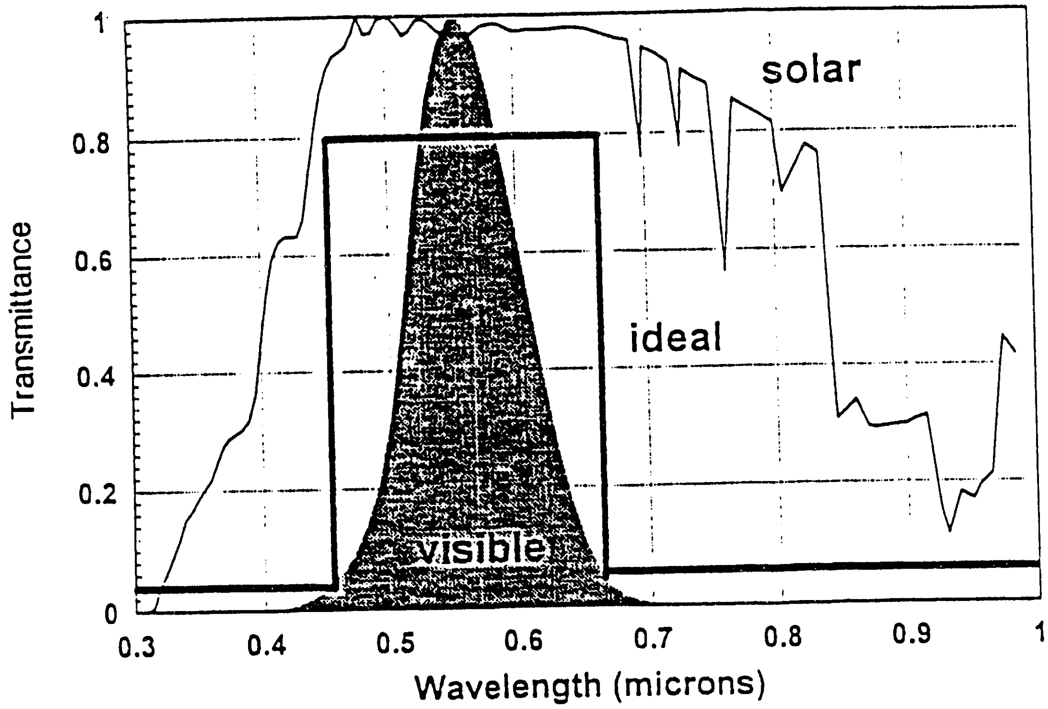

Figure 4. Ideal Cool Glazing for Automotive Applications.
Re: M. Rubin, LBL

Thermal comfort studies at LBL show significant increases in passenger compartment temperatures in automobiles exposed to summer sun for as little as one hour. These high temperatures place a great demand on air conditioning units which are expected to restore the passenger compartment to acceptable comfort levels within a few minutes. Electric powered automobiles of the future will pay a significant range penalty, see Figure 5, if large air conditioning units are required to achieve cool-down or maintain automobile interiors at acceptable comfort levels. Thus, the development of cost effective coatings that help manage thermal heat loads represent a major research focus.

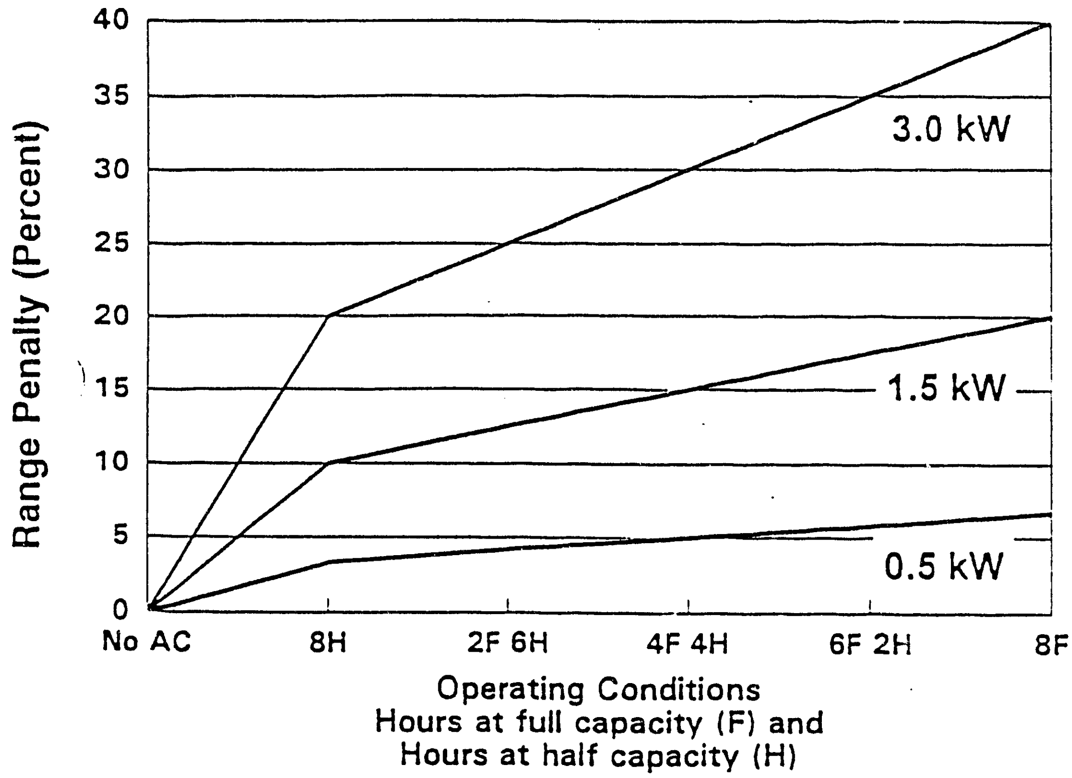

Figure 5. Range Penalty (Percent) for Air Conditioning Assuming a Fuel Efficiency of 1kWh/mi and a Range of 60 Miles.
Re: M. Rubin, LBL

The current trend of steeply sloped windshields means that requirements for visible transmission must be met at low angles of incidence with respect to the driver's eye, while minimizing infrared and UV transmission. Surface coatings must also be durable, scratch resistant, and able to survive exposure to the environment. Marketing issues, such as color and color rendition that are important for consumer acceptance, must also be addressed.

State-of-the-art cool glazings include tinted glasses and silver based multilayer reflective coatings that are laminated into the windshield. Multilayer reflective coatings give the best performance, but are also the most expensive. The two most important performance variables for solar control glazings are the visible transmittance and the shading coefficient. The shading coefficient is a measure of total solar heat gain and includes both the directly transmitted solar radiation as well as the indirect component of inward flowing heat due to absorption by the glazing. The optimal coating has a low shading coefficient and a high visible transmittance.

Some new development efforts are being directed at electrochromic devices which darken the windshield through the application of a small voltage potential. Electrochromics have three active layers: (1) an ion storage electrode; (2) an ion conductor; and (3) an electrochromic electrode. When the electric field is applied, ions move from one electrode to the other, and the visible light absorption of the optically active electrochromic layer changes, allowing the transmission of the glass to be varied. The process is totally reversible, which means that a darkened window can be made more transparent again by the flip of a switch. Electrochromic devices are currently more expensive than passive coatings, but research aimed at developing less expensive materials, improving device operation, and reducing manufacturing costs could greatly accelerate the use of this technology.

In general, the materials research issues for solar control coatings are improved electrochromics, angle selective coatings, durability, color control, and bendability. As we develop better performing materials to keep automobile interiors cooler, moisture condensation may become a problem. New coatings will have to be environmentally stable and not act as preferential surfaces for the nucleation of condensates.

It was noted that existing federal regulations present many problems for the auto industry due to conflicting requirements and lack of a clear-cut basis for establishing acceptable transmittance standards. The DOE does not have authority, or the mission, to become involved in such issues; however, as the DOE becomes more involved in addressing basic research problems associated with auto industry needs, they could become either a source or a conduit for the information needed to establish better standards.

John Bomback of Ford Motor Company and Ken Dean of General Motors led the sessions on identifying industry research needs. Additional comments from the auto industry were provided by Bob Tweadey (Ford) on system considerations, Ed Stanke (General Motors) on the impact of heat loads for passenger vehicles, Roman Surowiec (Ford) on ANSI/SAE standards and optical properties of various glasses, and Dennie Platts (Ford) on issues associated with mechanical durability. Desirable coating properties are summarized in Table II:

Table II. Glazing Requirements

Visible Transmittance
- High Visible Transmission (>70% in "Vision Areas")
- Extreme Angles will require Special Glazings
- No Added Haze

Selective Solar Spectrum Control
- Low Solar Heat Transmission
- Low UV Transmission

Color/Appearance/Aesthetics Issues
- Neutral vs. Tinted
- Rainbow Colors
- Privacy Masking

Additional Properties:
- High Scratch Resistance
- Chemical Durability
- High Adhesion
- Bendable
- Easily Cleanable

Currently, tinted glasses reflect up to about 44% of the incident solar radiation. While this is a quantifiable thermal benefit, the results are marginally perceptible to a driver. The application of a high-performance, multilayer dielectric coating can increase reflectivity to 60%, and this provides good thermal reduction benefits that are easily perceived. However, there are major differences in cost, i.e., tinted glass can be produced for pennies per square foot compared to dollars per square foot for the multilayer heat reflecting coatings.

Models of thermal energy balance for windshields have been developed to account for transmittance, absorption, bidirectional radiation, and interior/exterior convection. Two components of primary importance are the percent of incident solar energy transmitted and reflected vs. angle as measured from normal incidence, see Figure 6.

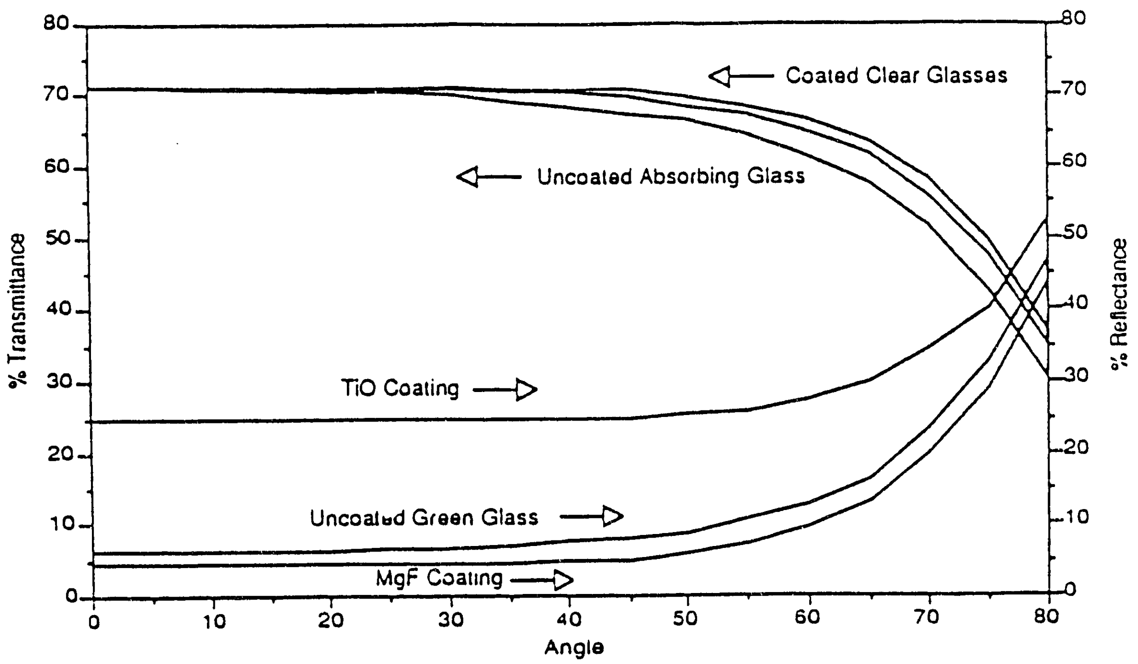

Figure 6. Percent Reflectance and Transmittance as a Function of the Angular Deviation from Normal Incidence. Re: Ford Motor Company, Glass Division.

The visible transmission for uncoated absorbing or coated clear glass barely meets the 70% transmittance requirement. Visible transmission drops below acceptable levels at angles of incidence greater than 30° for uncoated glass, and by 45° for coated glass. These curves underscore the importance of accounting for low angle transmittance in the development of new coating designs.

In addition to optical properties and thermal load management considerations, coating systems must be durable. For external applications, they may suffer particulate erosion damage, and they will be exposed to wind, hail, and various types of cleaning solutions. On interior surfaces, there will be fingerprints and soft drink splashes, which often mandate cleaning methods that employ vigorous rubbing. Little is known about damage to thin-film optical coatings, and there are currently no specifications which define hardness requirements, erosion performance, or environmental resistance. Damage modes need to be studied and better test methods must be identified.

Many of the issues discussed in this session apply equally to coatings for architectural glass used in advanced building concepts. It seems clear that common research efforts could benefit both applications. The research needs identified in this workshop were as follows:

	Composite Rating (1-5)
• Develop durable coatings for monolithic glass capable of rejecting 70% solar energy (35% or more reflection -35% or less absorption).	3.96
• Develop coating systems with high visible transmission at the driver's viewing angle, but low solar transmission at solar incidence angles.	3.58
• Develop materials and coating processes to improve the performance and manufacturability of electrochromic systems.	2.83
• Develop methods and processes for recycling coated glass.	2.45
• Develop improved modeling capabilities for predicting performance of solar and thermal control coatings.	2.78
• Perform research to establish the UV energy ranges that actually causes damage and to what materials.	3.57
• Study damage modes for solar control coatings to improve resistance to environmental attack, scratching, and erosion resistance.	3.39
• Develop models to improve selection criteria for solar coatings.	2.78
• Develop test methods for assessing durability, erosion resistance, and environmental resistance for coated glass and plastics.	3.52
• Study optical properties, e.g., transmittance reflection and absorption, which contribute to the database of prospective solar control coatings.	3.00

PROCESS MANUFACTURING ISSUES

Process and manufacturing issues are major considerations in the introduction of new coatings. Since cost is a primary issue, the auto industry cannot always select the highest performance material or one that is best from a technology standpoint. Instead, the most cost effective material consistent with product specifications and regulatory requirements will be chosen. A suitable manufacturing process must then be developed or an established coating technology utilized that will produce a quality product with a high degree of reliability.

The session was co-chaired by Bob McCune of Ford Motor Company and Larry Carol of A.C. Rochester. Keith Legg of the Basic Industry Research Lab at Northwestern University provided the technology overview.

Prospective new coatings for automotive applications will receive wider acceptance when processing issues associated with cost, reliability, and scale-up are adequately demonstrated. Promising areas where new opportunities seem to exist are: large scale production of small inexpensive parts, low friction coatings for gears and bearings, erosion resistant coatings for plastics, wear coatings for light metal alloys, corrosion resistant coatings for methanol containing fuel systems, radio frequency shielded coatings on plastics used in computers and sensors, and coatings for the fibers or fillers used in composite plastics.

A basic categorization of coating processes are summarized in Table III. Six specific technologies were reviewed in some depth. These were chemical vapor deposition (CVD), plasma enhanced chemical vapor deposition (PECVD), physical vapor deposition (PVD), plasma spray, plasma nitriding, and ion implantation.

Table III. Categorization of Coating Processes

Vapor Deposition	Chemical Vapor Deposition	Electro-chemical	Spraying	Ion
EB Evaporation	Reactive Gas	Aqueous	Detonation Gun	Ion Implantation
Thermal Evaporation	Metal-organic	Molten Salt	Electric Arc	Ion Beam Assisted
Sputtering	Plasma Enhanced or Assisted	Electroless	Metalizing	
Ion Plating	Laser Assisted	Electrophoresis	Plasma	
Reactive Sputtering	Microwave Assisted		Flame-powder Wire	

Sputtering was used as an example of a coating technology that has been successfully scaled-up and is currently being used to produce harder wear coatings for tool bits. This process technology may also be suitable for large-scale coating of windshields, or the production of wear coatings for gears and bearings.

The process of ion implantation has not received favorable attention from the auto industry because of relatively high production costs. However, a new variation of this process under development at Los Alamos National Laboratory called plasma source ion implantation is currently being scaled up, and the ability to control plasma distribution over large surfaces may enable the production of complex shapes at high through-put rates.

Several new developments in Japan that are currently at pilot plant stage were noted. These included: decorative coatings for architectural sheathing, coatings on stainless steel coil 35 cm wide x 300 m long, wear coatings of TiN and TiC produced by ion plating, thin Cr and Al_xO_y coatings made by sputtering, and the production of SiO_x by plasma enhanced chemical vapor deposition. These manufacturing advances, which are being implemented by a serious world competitor, highlight the need for pilot scale development efforts in the U.S. Most currently available coating systems are too small to properly scale to large volume manufacturing production, thus new demonstration systems are needed for this purpose. Attractive technologies include continuous-flow CVD, high rate deposition PVD, and multiple source plasma spray. Elaborate coating systems which combine multiple processes, see Figure 7, are also being put into production.

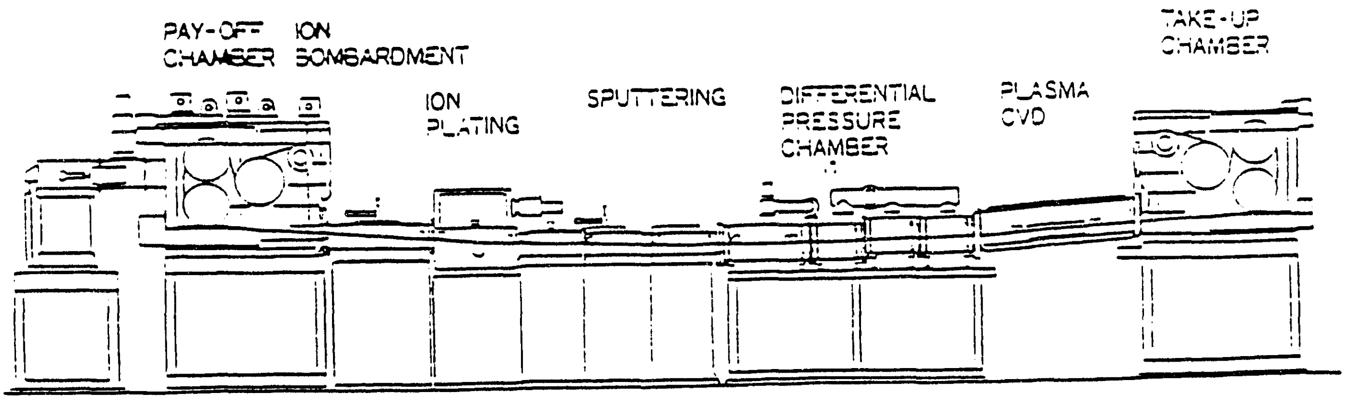

Figure 7. Multisource Continuous Process Coating System.

These are usually amenable to large volume through-put and provide useful flexibility since all processes don't have to operate simultaneously. The ability to produce multilayer and graded coatings are a major advantage of multiple process systems. Sometimes, process development efforts can be restricted either by the equipment or the specific parts to be coated. Processes often have to be revalidated for new deposition systems, different substrate sizes, geometries, or different materials. These steps might be alleviated by the development of better process models. There is a need to develop new sensors and sensor based control methodologies and integrate these with intelligent control packages.

Bob McCune (Ford) gave an overview of thermal spray technology which is a particularly attractive process for thick coatings. Manufacturing concerns include limited mass production experience, coating reliability, and the cost of machining and finishing steps. Better process monitoring and high rate material delivery systems need to be integrated with intelligent control methodologies. Thermal spray processes seem to be particularly suited for low-cost, high-volume, surfacing of materials.

The development of better coating techniques and more promising processes are not always the ultimate answer. Innovative solutions that couple the best material selection with the most effective processing approach can yield the biggest pay-offs. One example is the thermal spraying of steel onto an aluminum bucket tappet to reduce galling. Another thought, proposed by Bob McCune, was to coat magnesium with steel. Increased use of magnesium will help reduce automotive weight, but some applications have been limited by corrosion problems. While there may be other protective coatings, the auto industry has a large database and understanding of how to use steel technology which can be easily applied to component implementation and product introduction.

The strategic importance of sensors, which must be simple, inexpensive, reliable, and robust, was highlighted by Larry Carol of A.C. Rochester. Demands for new and better sensors to provide performance feedback during automobile operation are increasing. There is a need for expert systems with on-line monitoring and sensing capabilities to control coating deposition. For example, improved process control of plasma-sprayed coatings involves monitoring the plasma and controlling the properties of the particles being deposited, all in real time. On-line changes must be quantified and translated into a useful control algorithm which will enable immediate adjustment of the input parameters. Improvements in process control are needed to guarantee reproducible coating properties.

One example where process modeling could provide an important contribution is the injection molding of glass filled thermoplastics. If sensors can be found to accurately measure die cavity deterioration and component dimensional changes, models of the wear processes could be used to develop better coatings for improved dimensional control.

The research needs identified for the session on process manufacturing issues were as follows:

	Composite Rating (1-5)
• Study novel processing approaches which utilize and/or combine materials for which large experience and databases currently exist in the auto industry, e.g., magnesium coated with steel.	3.74
• Study manufacturability issues associated with coating light metals, e.g., aluminum, magnesium, and metal matrix composites, with wear resistance materials.	3.87
• Study prospects of surface strengthening light metals and metal matrix composites.	3.57
• Develop thermal barrier coatings designed to enhance thermal management in piston crowns and cylinder walls.	3.04
• Perform scale-up demonstrations of promising new processes, e.g., plasma source ion implantation sputtering.	3.52
• Develop new and novel low-cost processes for high volume surfacing of materials.	3.74
• Develop more reliable or better microfabrication techniques for integrated circuits.	2.68
• Study laser processing as a method for enhancing recyclability of coated components.	2.77
• Develop modeling and control methodologies to improve reliability and repeatability of selected coating processes.	3.48
• Perform generic studies to improve on-line monitoring and control systems with emphasis on new types of sensors and sensor base control capability.	2.95
• Perform simulation modeling of selected manufacturing processes prior to scale-up.	3.26
• Establish a technology exchange user center.	3.04

SUMMARY

The seven research needs with the highest overall composite ratings are summarized below. Three of these are under the category of Hard Protective Coatings for Plastics. Two were associated with Wear Coatings, and there was one each identified for Solar Control Coatings and Process Manufacturing. Surprisingly, none of the research areas identified in a previous DOE/NREL Workshop were rated as a top need in this particular survey.

Rank	Research Need	Composite Rating (1-5)
1.	Develop coatings and coating technologies for magnesium, aluminum, and lightweight metal matrix composites.	4.26
2a.	Develop coatings to protect plastics from automotive liquids and gasses, e.g., alcohol containing gasolines, antifreeze, brake, and transmission fluids.	3.96
2b.	Develop durable coatings for monolithic glass capable of reflecting 70% solar energy (35% or more reflection - 35% or less absorption).	3.96
4.	Develop coatings that will enhance the use of inexpensive dies for use in short production runs, e.g., injection molding of thermoplastics.	3.93
5.	Study coating techniques that will improve mar resistance, UV resistance, and moisture resistance of plastic materials.	3.92
6.	Study manufacturability issues associated with coating light metals, e.g., aluminum, magnesium, and metal matrix composites, with wear resistant materials.	3.87
7.	Develop coatings that improve abrasion and enhance environmental protection of plastics, e.g., diamond-like/a-C:H.	3.81

The number one research need was identified as the development of coatings for lightweight metals and metal matrix composites. This need was emphasized further by the highest rated processing issue (No. 6 overall) which was identified as the need to study manufacturability concerns associated with coating these same materials. Aluminum metal matrix composites have been considered for a variety of applications, and much research has been directed at processing/property relationships. Particulate reinforced alloys, which typically exhibit only modest improvements in mechanical properties, are the most economical to manufacture. Very little research has, thus far, gone towards the development of protective coatings to enhance or expand use of particulate composites in higher temperature engine applications such as cylinder bores. Principal coating issues involve adherence, differences in expansion coefficients, reactivity with the reinforcement phase, and the anistropy exhibited by some composite systems.

Three top research needs, which include the Nos. 2, 5, and 7 selections, were related to protecting plastics. The top priorities are for protection against automotive fluids, e.g. alcohol containing gasolines, brake and transmission fluids, etc., but improved abrasion and mar resistance, wear resistance, and resistance to UV damage are also important. Many of these requirements could conceivably be met by the development of low-cost, high-quality, diamond-like carbon coatings. The diamond-like character imparts good wear and abrasion properties as well as excellent chemical resistance. The development of compatible a-C:H type coating systems would seem to offer great potential for enhancing the use of a variety of low cost plastics if coatings can be produced economically and applied reliably over large surface areas.

The development of durable solar control coatings for monolithic glass was identified as the co-number two research need. These coatings will have to be capable of meeting national standard safety codes that require 70% visible transmission normal to the windshield surface. The technology currently exists, but the costs are generally too prohibitive; thus, cost effective solutions must be developed.

Coatings that will improve the die life and facilitate the injection molding of thermoplastics were also identified as a high priority (No. 4). Suitable materials and coating technologies are also currently available to meet this need, but coating reliability and cost issues will have to be addressed.

In responding to the questionnaire, several reviewers suggested a few additional topics. These are included in Appendix I for completeness.

APPENDIX I

The following is a list of six additional research needs that were added by reviewers while evaluating the four major categories in the text of this report. The ratings cannot be directly compared to the others listed in the text because they were not rated by other reviewers. They are, however, included here for completeness:

Potential Research Needs	Rating
• Friction reduction coatings for engine and transmission components.	5
• Surface coatings and their interaction with industrial and automotive lubricants.	4
• Develop a useful bench wear test for evaluation of surface coatings to be used in the engine components.	5
• Develop low emittance (reflective) coatings to reduce radiant heat absorption by plastic located adjacent to radiant heat source (Ex: plastic automotive floorpan over exhaust system).	5
• Develop the ideal window that rejects all UV and IR and transmits 75% of visible light.	5
• Develop durable, anti-reflective coatings for inside of windshield to reduce "viewing glare."	4

END

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