



Research and Development

SURFACE-COATING-FREE
MATERIALS WORKSHOP
SUMMARY REPORT

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SURFACE-COATING-FREE MATERIALS WORKSHOP SUMMARY REPORT

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ABSTRACT

Surface coating operations release approximately 15 percent of stationary area volatile organic compound (VOC) emissions as estimated by the 1985 National Acid Precipitation Assessment Program (NAPAP) emissions inventory. Emissions occur during the initial coating, as well as each time that a surface is recoated during the life of the object or structure. If materials or products could be developed that do not need coating during either manufacture or use (surface-coating-free materials) significant reduction in VOC and air toxic emissions could be achieved.

The U.S. Environmental Protection Agency, with the assistance of the Research Triangle Institute, sponsored a pollution prevention workshop exploring the concept of surface-coating-free materials and the potential impact of these types of materials on VOC and air toxic emissions from surface coating operations. The purpose of this report is to summarize the background and methodology used in planning the workshop, discussions that took place in the brainstorming sessions, and recommendations from the workshop. Included with the report are the technical papers that were presented as part of the workshop.

The workshop consisted of two parts; technical paper presentations and brainstorming sessions. Technical papers were presented by representatives of a varied group of industries that currently use or are developing surface-coating-free materials. The focus of the small group brainstorming sessions was to discuss specific topics related to the use of surface-coating-free materials. A major objective of these sessions was to identify and develop pollution prevention research concepts and recommendations for consideration by EPA that could expand the use of surface-coating-free materials. The brainstorming session topics were:

- regulatory and economic incentives and barriers to technology innovations,
- methods for enhancing the appearance and marketability of surface-coating-free materials, and
- potential pollution prevention research, development, and demonstration projects.

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1.0 Background

The national ambient air quality standard for ozone (0.12 ppm) is exceeded in over 100 geographic areas throughout the United States. Extensive reduction of volatile organic compound (VOC) emissions is required for attainment. The difficulty of dealing with stationary area sources has been a major obstacle to attaining these reductions.

Surface coating operations release approximately 15 percent of stationary area VOC emission as estimated by the 1985 National Acid Precipitation Assessment Program (NAPAP) emissions inventory. Many of the VOC and other emissions from surface coating operations are also air toxics having additional impacts on human health and the environment. Emissions occur during the initial coating, as well as each time that a surface is recoated during the life of the object or structure. If materials or products could be developed that do not need coating during either manufacture or use (surface-coating-free materials), it is anticipated that increased use of these products could result in reduction of VOC emissions. These emissions would be reduced not only from the applied coating but from other products required to use surface coatings such as solvents, surface preparation formulations, and paint removers. Some examples of commonly used surface-coating-free materials include vinyl siding, various forms of aluminum and other metals, many types of plastic parts ranging from computer casings to toys to military applications, and nonmetallic inorganic building materials such as brick and stone.

The U.S. Environmental Protection Agency's (EPA) Air and Energy Engineering Research Laboratory (AEERL) is responsible for a research program entitled, "Demonstration of Emerging Area Source Prevention Options for Volatile Organics." The program's goal is to reduce emissions from stationary area sources by developing, evaluating, and/or demonstrating pollution prevention options. The program has two project areas: (1) Alternative Coating Materials and Processes, and (2) Consumer Product Prevention Options. Each of the two project areas has several specific tasks. One of the tasks under the Alternative Coating Materials and Processes project area is the investigation of surface-coating-free materials.

The U.S. EPA, with the assistance of the Research Triangle Institute (RTI), sponsored a workshop exploring the concept of surface-coating-free materials, the potential impact of these types of materials on VOC and air toxic emissions from surface coating operations, and the means for promoting the surface-coating-free materials ethic.

This report summarizes the discussions and recommendations from the workshop. The discussion section is a result of notes that were taken during the brainstorming sessions. The individuals that participated in these sessions were from a wide variety of backgrounds and

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sponsoring organizations. As a result, a wide variety of viewpoints and priorities were expressed. The purpose of this report is to summarize and present the information as it was discussed and should not be construed to represent Agency policy.

2.0 Introduction

The workshop, entitled "Workshop on the Use of Surface-Coating-Free Materials for the Reduction of VOC Emissions From Surface Coating Operations," was held July 17-19, 1991, in San Diego, California. The purpose of the workshop was to explore the concept of surface-coating-free materials and discuss their use as a means of reducing VOC and air toxic emissions from surface coating operations. A main objective of the workshop was to identify research and development (R&D) opportunities for the further development of surface-coating-free materials (SCFM) currently being used by some industries and to recommend ways for increasing the use of such materials by other industries. In addition, the workshop offered a forum for the exchange and development of innovative concepts related to SCFM and technology innovation. A list of the workshop participants is contained in Appendix A.

There are a large number of materials (e.g., many metals and plastics) that are suitable for use uncoated. On the first day of the workshop, technical papers were presented by representatives of a varied group of industries that currently use or are developing some of these types of surface-coating-free materials. The papers were grouped into the following sessions:

- ◆ *Architectural Products,*
- ◆ *Applications for Uncoated Metals,*
- ◆ *Plastic Materials and Films,*
- ◆ *Development of Materials for High Temperature Applications, and*
- ◆ *Regulatory Perspective.*

A list of the speakers and copies of their papers are included in Appendix B.

The second day of the workshop consisted of a series of small group sessions. The focus of these sessions was identifying and developing research concepts that could expand the use of surface-coating-free materials. Each session lasted 2 hours, and the maximum number of participants per session was 12. The objective of each session was to discuss issues related to one specific topic and to develop a series of recommendations for consideration by EPA. The specific topics discussed were:

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- ◆ *Potential Demonstration Projects to be Considered by the EPA/AEERL Pollution Prevention Program,*
- ◆ *Methods for Enhancing the Appearance and Marketability of Surface-Coating-Free Materials,*
- ◆ *Regulatory and Economic Incentives to Encourage the Use of Surface-Coating-Free Materials and Barriers to Technology Innovation,*

At the end of the second day, the facilitators from each of the sessions summarized the highlights and recommendations from each of their sessions. Section 4 of this report is based on their summaries and notes taken throughout the day.

3.0 Methodology

The concept of using uncoated materials for various applications is not new. For example, many plastics, metals, glass, and nonmetallic inorganic materials are regularly used uncoated in a wide variety of applications. The concept of encouraging their use as a means of reducing VOC and toxic emissions from coating operations is, however, a new way of thinking. This may involve the substitution of materials that can be used uncoated for those that routinely require coatings. A common example of this is the use of vinyl siding as a replacement for wood siding in building construction. There are many corrosion- and ultra violet(UV)-resistant uncoated materials on the market and additional materials are emerging rapidly in the marketplace. Identification, discussion, and transfer of these materials to other applications as a replacement for materials that require coatings was a main goal of this workshop.

Because this is a new concept, the initial approach was to contact potential workshop speakers and participants by telephone. This provided us the opportunity to explain EPA's program, the concept of surface-coating-free materials, and the plans for the workshop. Representatives from the following industries were contacted.:

- *Automotive,*
- *Aerospace,*
- *Plastics and composite materials,*
- *Specialty metals,*
- *Aluminum and steel,*
- *Building and architectural,*
- *Paint and coatings,*
- *Wood furniture and wood products,*
- *Government agencies (Defense Department, National Aeronautics and Space Administration (NASA), and EPA),*
- *Pollution prevention and environmental groups, and*
- *Trade associations.*

Out of these contacts, the workshop speakers were identified and interest in and support for the workshop were established. In addition, approximately 2 months prior to the workshop, an

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announcement/registration flier was mailed to 750 potential participants.

Several of the individuals contacted expressed a concern that it appeared that EPA was promoting one industry (surface-coating-free materials) at the expense of another (paint and coatings). EPA understands the importance of paints and coatings in many applications and acknowledges that many recent improvements have been made within this industry in response to a growing concern over VOC emissions. However, there may be opportunities for material substitutions that result in a further reduction of VOC and air toxic emissions and pollution prevention in general. The purpose of this workshop was to introduce a new way of thinking and explore these opportunities with the final goal of improving the environment and reducing risks to human health.

The technical paper presentations served the purpose of introducing the concept of surface-coating-free materials by discussing some of the currently available materials and applications for their use. The papers were also useful for stimulating discussions and research concepts ideas on the second day of the workshop. The materials that were discussed covered a wide range of product types and applications.

The first paper was presented by Paul Bierman-Lytle of The Masters Corporation and included discussions on several different types of commercially available building products that do not require surface coatings. The first product discussed, autoclaved cellular concrete (ACC) has been used throughout the world for all types of construction ranging from single-family homes to large industrial, institutional, or commercial projects for over 70 years. It is a strong, lightweight, and versatile material that requires no surface coating. Currently it is not manufactured within the United States and must therefore be imported for use. An additional potential consideration with the use of this material is that it is produced from fly-ash which is known to contain low-levels of toxic metals. The safety of the use of fly ash as a component in building materials is currently being debated. A decision concerning this safety issue likely will have an effect on the widespread use of this product and other potential applications for fly ash within the United States.

The second product discussed during this presentation was cement-bonded particle boards that are manufactured in Finland from 30% wood chips and 70% portland cement. The uses for these particle boards include wall and ceiling panels, acoustic panels, special boards, drywall systems, and floor panels. The panels have a wood-veneered surface that does not require any type of surface coating. An additional type of surface-coating-free building panel that was discussed was a nonasbestos-containing roofing material similar in appearance to slate.

Pultruded products made from fiberglass reinforced plastic were discussed by Robert Dillner of Creative Pultrusions, Inc. Pultrusion is a continuous process of pulling fiberglass reinforcements (or other reinforcing materials) through a bath of thermosetting resin and into a heated forming and curing die. The curing process takes place within the die and is initiated by precise temperature control. The material solidifies in the exact shape of the die cavity as it is continuously pulled by the pultrusion machine. Specific strength, corrosion resistance, thermal, and other properties can be engineered for custom applications. Color is uniform throughout the

cross section of the product, thereby eliminating the need for many painting requirements. The resulting product is light weight, high strength, and relatively maintenance free. Application for extruded products include the electric, building/construction, and transportation industries.

Jim Katopodis from American Airlines discussed his company's history of flying and maintaining basically uncoated aluminum airplanes. Various types of aluminum alloys are available for a wide variety of applications. For the aircraft industry, the primary material property of importance is the ability to withstand many types of loads without being damaged. Additionally, the material must withstand cyclic fatiguing and be corrosion resistant. American Airlines has selected aluminum alloys that meet these necessary requirements. Included with this paper is a comparison of environmental and cost implications of painted versus nonpainted aircraft.

Another metal, titanium, can be used uncoated in a wide variety of applications and was the subject of a paper by Edward Mild of TIMET. Titanium is a generic term used to describe the entire list of commercially available grades of the metal and its alloys. In all its chemical compositions, titanium is resistant to corrosion by the atmospheric environment, seawater, and fresh water. Applications for uncoated titanium exist in many areas including: architecture, power plant flue gas desulfurization systems, and seawater applications. The initial cost of titanium products is higher than that of other metals such as aluminum or stainless steel however, its corrosion resistance is much greater and therefore will last longer, require less maintenance, and ultimately could result in lower costs over the entire life of a product. An additional factor to consider in the selection of titanium (and other metals as well) is the energy requirements (and resulting pollution) associated with production.

Bernard Appleman from the Steel Structures Painting Council presented data on successful and unsuccessful case histories of the use of weathering steel. Weathering steel is a high strength steel containing low amounts of chromium and other alloys. Under certain circumstances these alloys promote the formation of a tightly adhering dense oxide layer which precludes the need for any surface coating. This property provides distinct advantages over conventional carbon steel which requires a coating system for corrosion protection in virtually all exterior atmospheric environments. Applications where weathering steel has been used include rail cars, buildings, bridges, and utility poles. There have been some problems with use of this material in some of these applications and therefore caution should be exercised in the selection of this material. This paper discusses the advantages and disadvantages of this material as well as recommended applications and use procedures.

The next two papers, presented by Victor Rampelberg of Avery Dennison and John Rogers from DuPont, both discussed the use of polymer film coatings that can be applied to a wide variety of materials under controlled conditions. The films provide a weather and stain resistant surface for both interior and exterior applications. Some of the current uses for these films include automotive parts, residential siding material surfaces, decals for vehicle decorations, and aircraft interior surfaces. While these products technically stretch the definition of surface-coating-free materials (they in fact are coatings), their long life and controlled manufacture and application are likely to result in fewer VOC emissions than would result from the repeated and uncontrolled application of traditional coatings to the same products.

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The final technical paper was presented by Lawrence Hjelm from the United States Air Force Materials Laboratory. The topic of this paper was materials that are being developed for the National Aero-Space Plane Program. The goal of this program is the construction and flight testing of an experimental, fully reusable hypersonic aerospace plane. To meet this goal a variety of new materials are being developed and tested. Because one of the goals of the SCFM Workshop was to assist in the transfer of material technologies, it was anticipated that some of the materials being developed for this program would be applicable to other industries. The materials that were discussed included titanium alloys, titanium-based metal-matrix composites, carbon-carbon composites, ceramic-matrix composites, and copper-matrix composites. In all cases these materials are designed for very high temperature applications and are very expensive. Therefore their applicability is limited to other situations where material cost is not a prime consideration.

4.0 Workshop Discussion

Workshop participants were divided into small groups for the discussion sessions that took place on the final day of the workshop. The individuals that participated in these sessions were from a wide variety of backgrounds and industries. As a result, varying viewpoints and priorities were expressed. The following sections summarize these sessions and present the participants' recommendations.

4.1 Research, Development, and Demonstration Opportunities

One of the primary goals of this workshop was to identify potential research projects related to the use of surface-coating-free materials. Identified projects would then be incorporated with the list of potential demonstration projects to be considered for funding by AEERL. In addition to the identification of potential use of SCFM research projects, a significant amount of time was spent discussing potential research projects related to low- and no-VOC coatings. One of the discussion groups focused part of their time on the identification of important project selection criterion. These discussions are summarized in the following sections.

4.1.1 Potential SCFM Research, Development, and Demonstration Projects

The ideas that were generated in these discussion groups range from very general to very material- and project-specific. A recurring concept was that many materials currently exist that could be, and sometimes are, used without coatings. The group's recommendation for EPA research was to further expand the uses for existing materials rather than to develop new ones. Many other research organizations invest heavily in materials development. As these new material technologies become available, EPA could become involved in demonstration testing for different applications. In no particular order, the specific SCFM research projects identified during the brainstorming sessions were:

1. Environmental life cycle analysis of existing surface-coating-free materials.
 2. Investigation of opportunities for expanding the markets of currently available surface-coating-free materials.
 3. Material-specific focus groups.
 4. Improved accelerated aging tests for materials.
 5. Investigation of specific surface-coating-free building materials.
 6. Research to identify opportunities for the increased use of SCFM in the construction industry.
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7. Increased development and technology transfer of composite materials used in the aerospace industry.
8. Investigation and demonstration of the use of uncoated aluminum, and potentially other metals, in the transportation industry (i.e., work with the U.S. Postal Service to develop and test SCFM for postal vehicles).
9. Investigation of the process involved in producing and applying plastic film coatings.
10. Investigation of the use of weathering steel.
11. Conduct R&D on basic chemistry and physics of wood, plastic, etc.

4.1.2 Low- and No-VOC Coatings Research Needs

Although discussions of low- and no-VOC coatings were not a primary goal of this workshop, many of the participants felt that EPA should be conducting research in this area. Their thinking was that coatings are always going to be required in some applications; therefore focusing resources on improving coating technologies would be valuable. The following research areas were suggested:

1. Improvements in powder coating application technologies.
2. Demonstrations of UV-cured coatings and characterization of generated wastes.
3. Improvements in water-based coatings.
4. Demonstration of the plastic flame coat technology in various applications.
5. Evaluation of methods for improving the transfer efficiency in coating operations.
6. Investigation of surface preparation/priming requirements and opportunities for in-factory coating.
7. Organization of a workshop/conference on the topic of low- and no-VOC coatings.
8. Work with the U.S. Navy to test different coatings (and SCFM) on Navy vessels.

4.1.3 Project Selection Criteria

One of the groups felt that identification of project selection criteria was as valuable as the selection of actual projects. This group came up with a list of criteria that may be useful for EPA not only in the selection of projects for SCFM research but for other research areas as well. The criteria are the following:

1. Consideration of the total volume of VOC that can be reduced.
2. The opportunity for impacting multimedia problems.
3. Transferability of the technology.
4. Risk (success potential) versus benefits.
5. The need for sustainable development strategies.
6. Potential for outside co-funding.
7. Cost-effectiveness for utilization by small businesses and general public.
8. Time frame for implementation/completion of project.

4.2 Methods for Enhancing Appearance and Marketability of Surface-Coating-Free Materials

A large number of materials or material types are currently available and are used surface-coating-free. Expanded use of these materials in new applications involves more than overcoming technical barriers. Consumer acceptance may be difficult to gain for products that appear different from the norm.

These sessions focused on issues related to developing surface-coating-free materials with appearances and quality similar to traditional materials requiring surface coating. The three discussion groups covered a wide range of issues, often only tangentially related to the topic. This is partly due to the fact that manufacturers are very sensitive to appearance and marketability issues. In many cases, how the product looks is the critical element in the purchase decision, whether it is a \$15,000 automobile or a \$50 dinette chair. Consequently, any change in the appearance of the surface is viewed with skepticism by manufacturers.

The discussion groups raised questions rather than provided any answers. The key topics that emerged from the discussion groups included:

- ◆ Life-time of product
- ◆ Quality of final product
- ◆ Differences among markets
- ◆ Improved communications, EPA public relations, and technology transfer.

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- ◆ Appearance/marketability issues
- ◆ Management issues, and
- ◆ Regulatory environment.

Why is the coating needed? The answer to this simple question has complex ramifications. Often the answer is based on past experience or the "we've always done it this way" syndrome. However, it is critical to understand whether the purpose of the coating is appearance, marketing, customer demand, corrosion protection, chip resistance, or some other factor. In evaluating the use of materials, it is often important to look at the use of coatings and ask the following questions:

- ◆ *Why is the coating needed?*
- ◆ *Given these reasons, what approaches to eliminating the use of the coating are possible? Is elimination feasible for this use?*
- ◆ *Would changing the substrate be feasible?*
- ◆ *Could the uses be modified to not require a coating?*
- ◆ *Are there other components of the coating/application/substrate/use system that could be modified to allow for a SCFM approach?*

Trade-offs between SCFM and those with coatings have to be evaluated considering the useful lifetime of the product. In many cases, the coating provides a longer useful product life. For example, coating air conditioners in a beach environment prevents or at least reduces the effects of corrosion from salt spray. An alternative would be a reinforced plastic casing that required no coating and would be immune to salt water problems. If the product design dictates a short life, then a manufacturer may be unwilling to invest in a long-life component that may be more expensive. In the case of a product with a long design life, would it be appropriate to allow "more" VOC emissions to be released during the products production and/or use? Consumers may not be willing to pay the additional initial expense for longer-lived products.

Participants expressed serious concern about the extent, real or perceived, that product quality might be affected by moving to a SCFM. In many cases (e.g., automobiles), the coating is critical to the marketing and actual sale. The DeLorean, with its stainless steel body, was a car with a SCFM skin; however, consumers may prefer a shiny and lustrous red to a duller stainless steel. Issues discussed included how to determine when a quality finish is critical to the sale or, more importantly, the effective use of the product. Coating is critical to the performance of a non-stick frying pan yet is not critical to the performance of the exterior of a commercial aircraft fuselage. Even more challenging, is how to define product quality so that it can be evaluated with and

without SCFM. The groups concluded that quality is difficult to measure and assess objectively and can vary with the type of use.

A critical element related to coating issues is the cost of being wrong -- what if the SCFM doesn't work. For example, in developing alternative non-VOC finishes for wood or paper products, manufacturers have had problems producing a product with similar finish and "quality." Alternatively, essentially all products inside an airplane are coated, primarily for corrosion resistance because interiors of a plane are very susceptible to moisture buildup. Many of these parts are not readily visible making inspections more difficult. Consequently, manufacturers are reluctant to move to a SCFM product until it can be unequivocally demonstrated that it will be as resistant as the coated product. The consequences of a defective part are too serious.

SCFM marketability will vary depending on whether the market is consumer, industrial, government (nonmilitary), or military. Each market has different expectations of the same product based on how they plan to use it. Any program for promoting SCFM must recognize that different strategies should be employed for different market sectors.

In addition, there are several factors affecting appearance and marketability of SCFM. First, where is the coating applied: at the factory or in the field at the point of use of the product? The location of application may affect the extent to which a SCFM product could be developed or substituted for a coated product. Second, the type of substrate affects the need for coatings. Certain steels can be designed so as not to require coating while others would always require some coating for specific uses. Third, the point where most of the VOC releases occur needs to be identified. If there are low VOC emissions because of the type of application, etc., it may be appropriate to select other products for SCFM development. Finally, specifications set by large purchasers, such as the military and the automobile industry, have a significant impact on what their numerous small suppliers do. By working with the specification writers, regulators could facilitate the incorporation of SCFM alternatives into the specifications.

Two nontechnical areas were the source of much discussion: resistance to change and the effect of the regulatory environment on the choice of coating. All participants agreed that management attention and support were critical to considering SCFM as part of pollution prevention. Like everyone, managers and workers are resistant to change. This resistance needs to be addressed in developing innovative SCFM approaches. Otherwise, adoption of the new technologies may be slow in coming.

The discussion groups came up with the following series of recommendations related to the use of SCFM and low VOC coatings.

1. Establish regional technical innovation centers to promote and market surface-coating-free materials.
2. Improve education of professionals and the general public on alternatives to coatings.

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3. Standardize and accelerate coating testing and methodologies.
4. Develop systems approach to use/nonuse of coatings.
5. Conduct conferences and workshops for actual users, etc.
6. Conduct industry-specific focus groups.
7. Establish center for low-VOC products similar to the Southern California Edison energy conservation center.
8. Conduct research and development (R&D) to find non-VOC coatings approaches for coating needs.
9. Determine factors that influence marketability related to coatings and use them to guide R&D needs.
10. Develop an on-line reference for products and coatings with reduced or low-VOC releases.

4.3 Barriers and Incentives

The purpose of this session was to focus first on barriers to technology innovation and then on potential regulatory and economic incentives that could break down these barriers and encourage the use of surface-coating-free materials. Three groups of participants had the opportunity to take part in this discussion. Although these groups met separately, several common themes and/or concerns were expressed by all three.

4.3.1 Perceived Barriers

In no particular order, the major barriers identified are discussed in the following sections.

4.3.1.1 High development costs

Industry wants to do what is best for the environment but is reluctant to invest heavily in new product development unless the potential for profit is great. The expense associated with the development and marketing of a new product can be very high. The lack of revenue during the development stage makes it particularly difficult for smaller companies, without large research budgets, to invest the time and effort required to develop a new technology. In today's uncertain economic and regulatory climate, many companies are not interested in taking such risks.

4.3.1.2 New product uncertainty

Consumer acceptance is also a critical issue in the development of a new product or technology. A product has to be more than just environmentally friendly. It should also retain the same (or better) performance characteristics (at a competitive price) than the less environmentally friendly product that it is attempting to replace. In some cases, a new product may require users to modify their use patterns to get the best product performance. This may require some form of consumer education. Several workshop participants pointed out that this process can be very difficult -- resistance to change can be very great. Changing consumer attitudes often involves expensive marketing efforts.

4.3.1.3 Regulatory uncertainty

Regulatory uncertainty was a topic that received a great deal of attention in all of the discussion groups. Many participants expressed their frustration at attempting to develop new technologies with the ever-changing environmental regulations. Regional regulatory variations were stated by many workshop participants to also have a significant impact on the ability of a company to pursue technology advancements. Companies also have to consider the regulatory variations that exist from country to country. It was stated by several workshop participants that less stringent environmental regulations have resulted in businesses moving from the United States.

A similar type of barrier that was mentioned by the workshop participants is a perceived (or real?) non-uniformity of enforcement of environmental regulations, specifically with regard to small businesses. Some of the workshop participants expressed the opinion that enforcement personnel target large facilities and corporations and allow small firms to operate more freely.

4.3.1.4 Corporate bureaucracies

Red tape and bureaucracy exist in most institutions. Although many corporations are sincerely committed to reducing pollution and protecting the environment, making improvements in large operating systems can require perseverance and patience. Some workshop participants indicated that new and innovative concepts are sometimes stifled by corporate bureaucracy.

4.3.1.5 Technology transfer

Technology transfer is an issue critical to the advancement of the use of surface-coating-free materials. As stated, there are many materials (e.g. plastics, aluminum products and other metals) that traditionally have been used uncoated in a variety of applications. In addition, new materials are routinely developed. Often these materials are designed for one purpose and little effort goes into

expanding their applicability. Educating the producers and developers of these materials on the concept and potential benefits of surface-coating-free materials would likely be a very effective way to expand their use. Along with the transfer of materials technologies, there must be trust and cooperation between parties. Several of the workshop participants expressed the concern that competition between companies and the desire to have a competitive edge would have a negative effect on building the trust necessary for an effective technology transfer program.

4.3.1.6 Environmental life-cycle costs

The importance of performing environmental life cycle analysis was stressed many times throughout this workshop. A particular material or product may appear to have fewer adverse environmental impacts than another, but a detailed life cycle analysis may indicate the reverse to be true.

One primary issue in a life cycle analysis is the service life of the product. Several of the workshop participants indicated that a barrier to the use of certain uncoated materials is that no value is given to life cycle costs. In other words, a product that does not require repeated coatings may be more expensive initially. However, when the costs associated with the required recoating over the life of the product are factored into the equation, total costs may be competitive. It may be difficult to convince consumers to buy the initially more expensive product.

4.3.1.7 Military specifications

The aerospace industry was well represented at the workshop and identified the issue of military specifications for materials and coatings as a major barrier to innovation. All Defense Department contracts contain detailed specifications for all materials and coatings that are to be used as part of the project. The process required to modify these specifications is very expensive and time consuming, and therefore military specifications are very slow to change--even when a better (with regard to performance or environmental impacts) product is identified. Fears of many defense contractors are that if they would recommend a coating that was not part of the contract specifications, they would be labeled as being noncompliant, and they would endanger their existing or future Defense Department projects.

4.3.2 Regulatory and Economic Incentives

Regulatory and economic incentives that were discussed during the brainstorming sessions are briefly described in the following sections. No attempt has been made to prioritize or rank the incentives.

4.3.2.1 Tax Incentives

The use of tax incentives for research and development was considered by many of the participants to be one of the greatest incentives to encourage industry to develop new surface-coating-free materials. Many specific types of incentives were discussed such as tax credits based on a percentage of a company's R&D budget, tax credits for materials or VOC-related research only, and tax credits for pollution prevention technology implementations. An additional type of incentive discussed, without direct tax savings, is the use of other types of awards that could result in good public relations for a company.

4.3.2.2 User tax

The concept of a user tax or fee that is based on the actual costs (both production and environmental) of an item was recommended. Such a tax could be based on the VOC or air toxic content of a product and/or the amount of VOCs/toxics emitted during the production of a product. Such a tax or fee would give consumers a better understanding of what they are paying for and allow them to compare products and make decisions based on environmental impacts. A good example of the use of this kind of fee can be found in the auto industry.

A quality appearance and finish is critical to the sale of automobiles and other coated products. There is a great deal of competition between various manufacturers to develop better finishes that are environmentally compliant. Many of the finishes that have the most consumer appeal are the least environmentally friendly. An example of user fees could be a charge added to the sticker price of automobiles that are manufactured with these types of coatings. This fee should appear as a line item on the window sticker of each automobile. The window sticker would also indicate whether a low- or no-VOC coating had been used. This would allow consumers to compare finish types and appearances and make decisions based on a coatings' environmental costs.

4.3.2.3 Enhanced regulatory environment

Many of the workshop participants expressed the opinion that there is a need for improvements in the U.S. environmental regulatory system. Suggested improvements ranged from establishment of a import tariff on noncompliant foreign products (or products manufactured in countries that do not meet U.S. environmental regulations) to a reduction of the regulatory burden associated with making minor process changes at existing facilities. As mentioned in Section 4.3.1, many of the participants expressed the need for a "level playing field" with respect to environmental regulations. This issue was raised again pertaining to enforcement and regional regulatory variations.

4.3.2.4 Improved communications, EPA public relations, and technology transfer

A final incentive discussed at the workshop involved communication. Industry would like to be informed of and be involved in EPA programs and research. They are interested in the development of partnerships and co-funded research. Industry would also like to be included up-front on more policy development issues. It was suggested that EPA develop (or possibly improve and better publicize) information transfer programs. This could include information on research projects and results, opportunities for industrial participation, training/assistance, and public relations for the EPA concerning ways that they can help industry and vice versa.

5.0 Conclusions and Recommendations

The EPA/RTI workshop on surface coating-free materials provided an opportunity for discussion of a new pollution prevention concept that could result in reduced VOC and air-toxic emissions from coating operations. As can be seen from the list of participants (Appendix A), a wide variety of organizations/industries were represented. This diversity resulted in a unique forum for the exchange of information and differing viewpoints. The purpose of this document is to summarize the information from the meeting as it was discussed.

Although there are a wide variety of materials that are currently (and have been for a long time) used uncoated, the concept of increasing and encouraging their use as a means for helping to reduce VOC and air toxic emissions from surface coating operations is new. In the early stages of this project a great deal of effort was devoted to explaining this concept to potential workshop participants. Generally speaking most have agreed that it is a good concept however, it is going to take persistence and time for it to be understood and adopted on a wide basis. It was recommended that EPA continue to advance the concept through the use of workshops, meetings and briefings with potentially involved industries and trade associations, and paper presentations at appropriate meetings and conferences.

In conjunction with the further development of the concept of surface-coating-free materials, there needs to be an investigation of the life-cycle environmental impacts of the use of specific materials. On the surface, it may appear that one material is less polluting than a similar product. However, a complete investigation of the product's entire life cycle needs to be performed to ensure that adverse environmental or health impacts are not associated with different stages of a material's production, use, disposal, etc. A recommendation from the workshop was that EPA perform a life-cycle analysis on several currently used, coated materials and alternative surface-coating-free materials. The results from these analyses could then be compared to determine which product is less polluting.

Coatings serve many very important functions and will continue to do so in the future. Therefore, EPA should focus attention on the development and demonstration of low- and no-VOC coatings in addition to surface-coating-free materials. Many of the workshop participants recommended that EPA conduct additional workshops in these areas. Specific recommendations concerning content of additional workshops varied. Some indicated that a large broadly defined conference encompassing coating technologies and surface-coating-free materials would be the most appealing. Others indicated that small specifically focussed industrial group meetings might result in the best exchange of information.

Additional specific research projects were recommended by the workshop participants. These projects were discussed in Section 4.1.

Appendix A

Surface-Coating-Free Materials Workshop Participants

Attendees List
Surface-Coating-Free Materials Workshop
July 17-19, 1991
San Diego, California

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Appendix B

Paper Presentations

The following is a list of the speakers at the workshop. Page numbers for each of the papers are included in parentheses after the title.

SESSION 1 ***Architectural Products***

Dr. James M. Lents, Executive Officer
South Coast Air Quality Management District

Keynote Address
*Use of Surface-Coating-Free
Materials*

Mr. Paul Bierman-Lytle
The Masters Corporation and
Environmental Outfitters

*Surface-Coating-Free Materials for
the Reduction of VOC Emissions
(B-3 through B-11)*

Mr. Robert Dillner
Creative Pultrusions, Inc.

*Applications for Pultruded Products
(B-12 through B-16)*

SESSION 2 ***Applications for Uncoated Metals***

Mr. Jim L. Katopodis
American Airlines

*The Use of Uncoated Aluminum as
the Major Component of American
Airlines Aircraft (B-17 through B-22)*

Mr. Edward E. Mild
TIMET

*Titanium-Compatible with the
Environment (B-23 through B-49)*

Dr. Bernard R. Appleman
Steel Structures Painting Council

*Uncoated Weathering Steel for
Bridges and Other Structures
(B-50 through B-58)*

SESSION 3
Plastic Materials and Films

Mr. Victor H. Rampelberg (Speaker)
Avery Dennison

Painting Thermoplastics with a Film
(B-59 through B-66)

Mr. Charles H. Fridley (Co-Author)
Avery Dennison

Mr. John H. Rogers, Jr.
DuPont Company

TEDLAR PVF Film Coating
Applications (B-67 through B-70)

SESSION 4
Development of Materials for High Temperature Applications

Mr. Lawrence J. Hjelm (Speaker)
U. S. Air Force Materials Laboratory

Materials Related to the National
Aero-Space Plane (NASP)
(B-71 through B-78)

Mr. Terence M. F. Ronald (Co-Author)
U. S. Air Force Materials Laboratory

SESSION 5
Regulatory Perspective

Mr. Charles H. Darvin
U. S. Environmental Protection Agency
Air and Energy Engineering Research Laboratory

The Pollution Prevention Challenge
to Scientists and Engineers

SURFACE-COATING-FREE MATERIALS FOR THE REDUCTION OF VOC EMISSIONS

Author

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I. AUTOCLAVED CELLULAR CONCRETE (ACC)

ACC is a building material developed by a Swedish architect, Johan Axel Ericksen, and patented in 1928. It is a superior, fine-grained, porous concrete material that is suitable for all types of construction, ranging from single-family homes to large industrial, institutional, or commercial projects.

ACC is manufactured and used for housing and commercial/industrial buildings in many countries throughout the world. YTONG, of West Germany, began manufacturing ACC in 1929 and presently has 40 plants in various countries. SIPOREX, of Sweden, has plants in 23 countries around the world. HEBEL, of West Germany, has 32 plants in 12 countries. H & H, of Denmark, has 6 plants in Europe. THERMALITE has 7 plants in the U. K. Currently, several of the European companies are exploring the U.S. market. WEYERHAEUSER is actively involved in developing the ACC industry in the United States.

The Department of Technology Education, West Virginia University, is involved in a diffusion/adoption project to promote the establishment of an ACC manufacturing plant in West Virginia. Under the direction of Professor Edward Pytlík, several papers have been prepared for the introduction of ACC into the U.S. market. These papers include: *ACC, The Building Material For The 21st Century*, and *ACC, A Useful Shelter Technology For Developing Countries*. According to HEBEL, of West Germany, ACC has met and complied with U. S. building codes and has several test projects under way in Florida. HEBEL is planning on opening manufacture of ACC by 1993 in

Surface-Coating-Free Materials for the Reduction of VOC Emissions

the United States. However, currently, the closest manufacturing plant of ACC is located in Mexico.

MANUFACTURE OF ACC

The raw materials required for ACC are finely ground sand or fly-ash, lime, water and a small amount of aluminum paste or powder. Research and development in the manufacture of ACC have led to the replacement of sand with fly-ash (pulverized fuel-ash) by as much as 100% in some cases. Fly-ash is a by-product from coal-fired electric generating stations. In 1985, more than 48 million tons of fly-ash was produced in the United States of which only 5.1% was used in concrete products.

The raw materials are mixed into a slurry and tapped into greased molds up to two-thirds of their depth. For large reinforced units, rust-protected reinforcement nets are positioned into the molds before casting. The aluminum paste or powder creates a chemical reaction releasing hydrogen gas, which aerates the mixture producing millions of microscopic nonconnecting cells. Depending on the process used, it takes from 20 minutes to 2 hours for the mixture to harden enough to be cut and shaped.

This mixture is then cured in an autoclave for 10 to 12 hours and the finished product, ACC, is 80% to 90% air by volume.

PROPERTIES OF ACC

LIGHTWEIGHT: Because of its porous structure, ACC weighs less than one quarter of the weight of traditional concrete. This reduces transportation costs, worker injuries, and installation time.

COMPRESSIVE STRENGTH: ACC has twice the compressive strength of air-cured concrete of identical composition and density.

THERMAL INSULATION: Because of the totally enclosed air cells distributed evenly throughout its structure, ACC provides its own thermal insulation and can substantially reduce heating and air-conditioning costs.

WORKABILITY: ACC can be easily drilled, sawn, chased, or nailed with ordinary woodworking tools.

SOUND ABSORPTION: ACC provides quiet interiors for housing and protects against production noise in industrial settings.

FIRE RESISTANCE: ACC is purely mineral in composition, and thus it is noncombustible. It provides twice the fire resistance of traditional concrete.

EARTHQUAKE RESISTANCE: Tests have proven that ACC performs excellently in seismically active areas.

VERSATILITY: ACC can be manufactured in various forms: large precision blocks, lightweight partition panels, load bearing and non-load bearing lintels, reinforced units for floors, roof slabs and wall units, profiled blocks or units with tongue and groove joint faces.

INSECT RESISTANCE: ACC is inorganic and therefore 100% termite resistant and free from insect problems.

COST COMPETITIVE: ACC has proven to be cost competitive with traditional concrete when access to ACC is regional as with traditional concrete.

HEALTH HAZARDS: ACC emits no VOCs, contains no formaldehyde. It can pose a "dust hazard" when it is being worked, similar to wood dust, sheetrock dust, or other concrete dust products.

SURFACE COATING FREE: ACC requires no surface coating and is manufactured in cement grey or white. However, it can accept most surface coatings, such as plaster, stucco, wood or masonry veneer, or paints (such as white-wash).

APPLICATIONS OF ACC

Although ACC has been in production for over 70 years, and worldwide production exceeds 24 million cubic meters, it is not currently manufactured in the United States.

However, in the United States, there are more than 2 dozen buildings made from imported ACC. These include a 750,000 ft² building in Rhode Island in 1964; a 40,000 ft² building in Orlando, Florida, in 1986; and test facilities in Florida and at West Virginia University. ACC has been approved as a building material by HUD and BOCA.

The Masters Corporation, of New Canaan, Connecticut, is planning to utilize ACC in ECO-tourist hotels in Costa Rica and in southern California, as well as in seven 21st Century environmental buildings in Michigan beginning in 1992.

Environmental Outfitters, of Connecticut and California, specializing in catalog, retail, and wholesale of 21st Century environmental building materials, is investigating ACC to include in its inventory for sales in the United States and Canada.

LIMITATIONS OF ACC

Currently ACC is not available in the United States unless one imports it from Europe. Once available, the product will have to gain acceptance among the conventional concrete industry, installers, engineers, building inspectors, and architects. Given its track record in Europe for over 70 years, and its good environmental report card, acceptance in the United States could be earlier than later.

II. ELAM OY CEMENTIOUS BUILDING PANELS

ELAM OY products are ready-surfaced fire-retardant wall and ceiling panels used mainly for public interiors. Cement and gypsum-bonded particleboards are used as core material, but for the

purpose of this workshop, I will focus on the ready surfaced wood veneer particleboards.

MANUFACTURE OF ELAM BOARDS

ELAM cement-bonded particleboards are manufactured in Kuusankoski, Finland. Their products have been approved in Finland, Sweden, Denmark, Norway, Iceland, UK, Germany, France, Netherlands, Spain, and the Soviet Union. Projects have included:

- Sports Center in Nakkila, Finland
- Church of Maria, Helsinki, Finland
- Sheraton Hotel, Gothenburg, Sweden
- Concert Hall, Mikkeli, Finland
- Culture Centre, Espoo, Finland
- Office of Haka Oy, Helsinki, Finland
- Ikvik-Finnsauna, Stockholm, Sweden
- Ministry of Gas, Soviet Union
- Music Conservatory, Madrid, Spain
- Over 20 Hotels in Soviet Union

The products are currently not available in the United States or Canada, except through import. Environmental Outfitters is currently establishing a distribution of the products via its retail centers in Santa Monica, California, and New York City.

COMPOSITION OF ELAM PANELS

ELAM cement-bonded particleboard consists of wood chips (30% dry weight) and portland cement (70% dry weight). The boards are sanded and thickness calibrated suitable for requested use or for surface coatings. The boards can be installed as they are from the mill, or they can be covered with decorative melamine, wallpaper, high-pressure laminate or paint, either at the mill or on site.

Edges can be grooved at the mill for appropriate fixing methods. Installation brackets and joiner hardware is also available from ELAM.

The products are autoclaved and emit no toxic fumes or VOCs. They are formaldehyde-free unless surface coatings which contain formaldehyde are requested.

PROPERTIES OF ELAM PANELS

Density:	1.250 kg/m ³
Thickness Swelling:	1% 2 hr in water
Sound Reduction:	Good
Thermal Conductivity:	0.35 W/m ² K
Resistant to Fungi and Termites	

Alkalescence:
Weather Resistant
Moisture Resistant

12 pH value

USES OF ELAM PANELS

The uses of ELAM cement-bonded particleboards include wall and ceiling panels, acoustic panels, special boards, drywall systems, and floor panels.

The Masters Corporation currently is only specifying the use of wood-veneered cement-bonded particleboards for interior wall and ceiling panels, as well as acoustic panels.

LIMITATIONS OF ELAM PANELS

The boards are currently not available in the United States, although efforts by ELAM OY are under way to introduce the panels to North America.

The boards are heavy because they are comprised of wood chips and portland cement and thus have installation concerns; however, because they are designed to be fitted into each other or into specially designed hardware, installation is expedited. Also, since surface coatings are not required, several steps are avoided that reduce cost and maintenance.

Pricing is expected to be competitive since the product offers many one-step features. Boards can be made to meet U. S. customary dimensions and are offered with a variety of thicknesses.

The wood-veneered panels are very handsome, easy to maintain, require no coatings, satisfy most fire requirements, and are good sound barriers. These features make up for the premium in initial cost and newness to the market.

III. ETERNIT CEMENTIOUS BUILDING PRODUCTS

ETERNIT produces a family of nonasbestos panel products used in building construction and for industrial components. These include:

- ◆ Roofing Slates
- ◆ Glasweld
- ◆ Eterspan
- ◆ Eflex
- ◆ Eterboard,
- ◆ Profile 6
- ◆ Substrate 500
- ◆ Facad.

For the purpose of this workshop on surface-coating-free materials which contribute to the reduction of VOC emissions, I will focus on ETERNIT roofing slates, Profile 6, Facad and Glasweld. However, I will briefly describe the other products as well.

Surface-Coating-Free Materials for the Reduction of VOC Emissions

ETERSPAN is a medium-density calcium silicate panel which is used as a substrate for the direct application of synthetic and cementitious coatings, ceramic tile and thin brick. It is widely used as a component in prefabricated wall panels and in on-site studwall assemblies.

EFLEX, the uncoated substrate for GLASWELD, is the highest quality, high-density, nonasbestos, fiber reinforced cement panel available. Uses include substrate for architectural metals, ceramic tile, stone and stone aggregate. Industrial uses include laboratory fume hood linings and electrical components.

ETERBOARD is a medium-high-density calcium silicate panel developed as a direct replacement for commodity asbestos cement panels. Its applications range from residential to commercial and industrial uses. It is often used as a component panel facing and as a core for laminated panels.

SUBSTRATE 500 is a ceramic tile backer board, strong, light weight and highly water resistant. It eliminates the problem of gypsum board or gypsum plaster breakdown in shower and tub locations.

GLASWELD, an architectural facing panel is used for facades, curtainwall cladding, fascias and interior applications. It is an opaque mineral fiber reinforced cement panel available in a spectrum of permanent designer colors.

FACAD is a slate-textured cladding panel fiber-cement with a GLASWELD surface or uncoated. Uses include fascias, facades and interior walls.

ROOFING SLATES are fiber-reinforced cement shingles. Available with an authentically textured surface, they are supplied in blue-black, grey-green, and rose grey in two sizes. They can be used for high-quality roofing, fascias, facades and mansards.

PROFILE 6 is a corrugated, fiber-reinforced cement sheet used for roofing, siding and partitions in industrial, commercial and institutional buildings. It is also a major component in cooling tower construction.

MANUFACTURE OF ETERNIT PRODUCTS

ETERNIT, headquartered in Brussels, Belgium, is one of the world's largest producers of building materials. The company is a leader in fiber-reinforced cement products and inorganic color systems and has plants and sales offices in over 50 countries. ETERNIT has recently developed technologies which enable it to produce nonasbestos cement products which retain the superior physical characteristics of asbestos but do not contain that hazardous material.

ETERNIT, INC., located in Reading, Pennsylvania, was initially organized to market GLASWELD. The company has recently established the Standard Products Division to market a line of commodity and specialized mineral-fiber-reinforced panels: Elfex, Eterspan and Eterboard.

The U. S. Eternit company has established a nationwide network of distributors and representatives. Eternit has in-house technical support and is backed by the resources of the parent company in Belgium.

FEATURES OF ETERNIT ROOFING SLATES

PERFORMANCE: Eternit Slates meet the requirements for Class A usage in accordance with ASTM E-108 (83) when installed over 5/8-inch sheathing. A test report by an independent laboratory is available upon request.

WATERPROOF: Prolonged soaking does not affect the slates. The stone-like product provides 100% integrity to properly designed and prepared roofs.

PERMANENCE: Eternit slates stand up to generations of freeze-thaw, hail and standing snow. Industrial effluents, salt spray, termites, vermin or fungus have no effect on the slates.

NONASBESTOS, NON-VOC EMITTING: Eternit's unique formulation of fiber-reinforced cement does not present a health hazard to consumers or installers.

WARRANTY: Protected by a 30-year nonprorated warranty.

IV. AIR KRETE INSULATION

AIR KRETE is an ultralight cementitious foam insulation that is being marketed, following 10 years of intense research and development, as a viable alternative to urea formaldehyde and other foamed-in-place insulation products. Headquartered in Weedsport, New York, AIR KRETE is distributed exclusively in the United States via a network of licensed manufacturers. Efforts are being made to export the product to Europe and Canada. Patents for AIR KRETE have been issued.

COMPOSITION OF AIR KRETE INSULATION

AIR KRETE is a formulation of two proprietary components, water, calcium chloride, and magnesite, which when expanded with compressed air, produce a foam primarily designed for installation in cavity fill applications. It can be installed in any cavity through a 5/8" to 2 1/8" diameter hole, and its flow properties ensure confidence in filling all voids. Bulgy or cracked walls, due to produce expansion, are eliminated because AIR KRETE does not expand after leaving the application equipment.

AIR KRETE has successfully been installed in noncavity applications.

MANUFACTURE OF AIR KRETE INSULATION

AIR KRETE insulation is made on site by trained installers. The various components are shipped to the nearest distributor, who, in turn, delivers it to the contractor/installer.

Surface-Coating-Free Materials for the Reduction of VOC Emissions

AIR KRETE has enjoyed quick compliance with local code authorities due to its unique features. It has been installed in HUD buildings, U.S. Army projects, Union Carbide, Safeway Foods, high schools across the United States, and many hundreds of residences.

FEATURES OF AIR KRETE INSULATION

Chemical Analysis:	inorganic nontoxic no asbestos no irritative fibers no VOCs during or after installation minimizes corrosion pest resistant ozone safe no formaldehyde no fluorocarbons moisture resistant
Fire Characteristics:	firewall test (E119) no toxic fumes noncombustible no smoldering ASTM-84-81A flamespread 0 fuel contributed 0 smoke density 0 firestopping approved
Thermal Conductivity	R-value 3.9 per inch zero shrinkage ASTM C951 no expansion total fill characteristics nonsettling
Acoustical	8 to 9 decibel improvement (50%)

LIMITATIONS OF AIR KRETE INSULATION

Cost:	approximately 28¢ to 50¢/bf
Installation:	requires available technician requires trained technician
Resilience:	friable at the density of 2 lb/ft ³

Moisture:

will absorb moisture even though it doesn't affect *structure*
it does not hydrolyze as a result of vapor flow transmission,
high heat or humidity

APPLICATIONS FOR PULTRUDED PRODUCTS

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Pultrusion is a continuous manufacturing process utilizing glass or fibrous reinforcement in a polyester or other thermosetting resin matrices. Pre-selected reinforcement materials like fiberglass roving, mat or cloth are drawn through a resin bath where all the materials are thoroughly impregnated with a liquid thermosetting resin. The wet-out fibrous laminate is formed to the desired geometric shape and pulled into the heated steel die. Once in the die, the resin cure is initiated by controlling precise elevated temperatures. The laminate solidifies in the exact shape of the die cavity as it is being continuously pulled by the pultrusion machine. Specific strength characteristics can be designed into the composite optimizing laminate performance for a particular application by strategic placement of high performance reinforcements. Color is uniform throughout the cross section of the part, eliminating the need for many painting requirements.

The pultrusion process produces parts with constant cross-section shapes. Many forms of reinforcing material (examples: rovings, continuous strand mats, woven and nonwoven fabrics, and a variety of surfacing veils) plus a wide selection of resin systems allow the designer versatility in engineering the pultruded structural composite to meet the end-use requirements in the most cost-effective way. Cost of the product is also minimized by low tooling cost and the low labor content of the pultrusion process. Because the reinforcing materials are processed in continuous forms, product properties are very consistent. Last, the length of the pultruded part is limited only by shipping considerations.

Pultrusion is a continuous process making constant cross-section profiles. The process is designed to pull flexible reinforcements through a liquid resin bath into a heated die. A pultrusion process line is long and narrow with lengths from 40' to over 80' with the width being 5' to over 20'. The overall space requirement depends primarily on the size and number of the creels used to hold the reinforcements.

A typical pultrusion line consists of six basic stations:

- ◆ *Reinforcement dispensing*
- ◆ *Resin impregnation*
- ◆ *Performing*
- ◆ *Heated die curing*
- ◆ *Clamp/puller*
- ◆ *Cut-off.*

For reinforcement dispensing background, in the first station, continuous fiberglass roving is dispensed from center-pull packages that sit on shelves called creels. The roving is guided through porcelain eyelets that eliminate static buildup and fuzzing. The roving then passes through a carding index that orients the fibers prior to entering the resin bath. Other reinforcements such as mat, veils, carbon fiber tows, etc., are routinely used and are dispensed on the rolls.

Resin impregnation is a reinforcement package that passes through the wet-out tank. Pan guides function within the resin bath to keep the roving separate and to maintain tension on the strands to permit the resin to wet-out each fiber. The resin bath can be of the standard dip tank design or the straight-through resin pan as for hollow sections or complex profiles. Pressure impregnation is a third method used for unique application. In this method, the resin polymerization all occurs inside a closed die. This area is the main concern for VOC release in the form of fugitive styrene vapors. However, because of the closed die, processing/pultrusion is typically lower than spray up or winding processes (with the profile chops having releases of 3% to 5% and rod producers approaching 0.8%).

When the reinforcement package exits the resin bath, it then passes through a series of bushings or forming guides that are designed to strip off excess resin and guide the uncured composite into the final composite shape. This is called the performing section.

The heart of the pultrusion process is the curing die. After the resin-impregnated reinforcement package leaves the final pre-shaping section, it enters a heated steel die or dies that are in the shape of the finished composite. The dies range in length from 30 to 60 inches and are heated either by electric strip heaters or plates on the top and bottom of the die surfaces. The interior die surfaces are generally chrome plated for increased die life and improved surface finish.

The term "pultrusion" comes from the fact that the composite is pulled through the entire process by a gripper/puller system. There are two different types of gripper/pull systems used, the reciprocating clamp design and the opposed tread caterpillar-tractor type. The former method utilizes two identical pullers that operate in tandem to alternately grip and continuously pull the profile through the process. The puller process is mainly used for mat/roving composites in which urethane cleats grip the part and pull it through the mold.

The final station is the cut-off station of the pultrusion process. This station consists of a diamond abrasive cut-off saw. This saw is synchronized with the movement of the pullers and is activated by a preset cut-to-length limit switch.

The raw materials that make up the bulk of pultruded products consist mainly of reinforcement and matrix. The reinforcements include glass fibers in the form of continuous roving, continuous strand mats, knitted and woven fabrics, tapes and cloths. More exotic reinforcements include

Applications for Pultruded Products

carbon fiber, aramid, boron and several new thermoplastic fibers and veils.

Fibers are formed from several glass compositions, the most common of which are A (alkaline), C (chemical), E (electrical), and S (strength). Continuous roving of the E-glass type comprises the bulk of the reinforcement used in pultrusion. Continuous roving is a collection of filaments coated with a sizing that is compatible with the resin system and brought together into a single strand called an end.

Bulk roving is also used in pultrusion. This product form is designed to improve the transverse properties in localized areas of pultruded composites where mat cannot be formed.

C-glass, A-glass and thermoplastic are some of the surfacing materials used in pultrusion. Polyester veils are the most commonly used surfacing fabrics and provide an 8- to 11-mil resin-rich barrier that improves corrosion resistance, reduces fiber exposure on the surface, and improves resistance to UV attack. Surface veils have been processed which withstood 4,000 hours accelerated weathering with only a slight loss of gloss.

The two major families of resin matrices are thermoset and thermoplastic. Today the majority of resin matrices used in pultrusion are thermoset. Several thermoset resin types are used in pultrusion with standard polyester and flame-retardant polyester resins being the most widely used. However, new applications and processing technologies are increasing the demands for vinylesters, epoxies, flame-retardant vinylesters, low shrink systems and even thermoplastic resins. The choice of the resin will determine the degree of corrosion resistance, the upper operating temperature limit, performance in fatigue applications, and to a limited degree, the mechanical properties of the pultruded laminate. The reinforcement primarily determines the strength and electrical properties of the pultruded laminate. Fillers may be added to improve flame retardancy and processability and to reduce cost.

Pultruded composites are generally divided into two parts. One being all unidirectional roving parts (rod and bar stock), and two being continuous strand mat/unidirectional roving parts (shapes and flat sheet). Typically, all unidirectional roving parts have superior mechanical properties in the longitudinal direction, where glass contents range from 65% to 85% by weight.

These values for shapes, flat sheet and rod/bar stock are taken from ASCE's Structural Plastic Design Manual and tell you the range of properties one might expect with fiberglass polyester pultrusions.

The reinforcements in flat sheet are mat and roving. Flat sheet is commonly produced in thickness up to 1" and widths up to 56", with 48" being standard.

Pultrusions are used in a variety of markets, the first being the electrical industry. This is one of the largest markets for pultruded composites because of their high strength-to-weight ratio and excellent dielectric insulation properties. The use of pultruded side rails have almost completely antiquated the wooden ladder and the electrical nonconductivity of fiberglass has allowed almost complete replacement of the aluminum ladder by electrical utilities. The color in the ladder channel is molded through the laminate. Orange and yellow are safety colors and can be seen on almost any utility truck today. Usage of pultruded products are found in pole line hardware

where pultruded tubes and rods are used for tools for work on high power lines because of the added benefit of being electrically nonconductive.

Also, the pultrusion process is used to manufacture structural components which will withstand severe corrosive environments. All fiberglass products can be considered to be corrosion resistant with the choice of the resin determining the degree of corrosion resistance. Grating manufactured with pultruded components is also the strongest fiberglass grating on the market. The method of construction of the pultruded shapes ensures excellent corrosion resistance. Bearing bars and cross rods are pultruded and fabricated into grating for many industries such as electroplating, water and waste, marine, offshore and others.

Another example of the use of pultruded products for corrosion resistance is mist eliminators. Louver blades separate vapors and solid particles from stack emissions such as in coal burning utilities. Pultruded blades are replacing wood, stainless steel and thermoplastics giving an increased usable life.

In the construction industry pultruded products are viable materials because of their strength, light weight, corrosion resistance, molded-in color and thermal and electrical insulation. For example, pultruded components make nonmetallic window frame and sash lineals the ultimate in performance. These components are quickly replacing aluminum and other competitive materials with a new generation of thermally efficient, dimensionally stable window frames.

Another example for the construction industry is roof supports. Roofing systems with a four-to-one safety factor for wind and snow loads and the added benefit of corrosion resistance have been installed for pole enclosures.

Pultrusions have long been accepted in the transportation market. Pultruded panels run the entire length of the Intercity Transit Bus and provide insulation and dent resistance as well as long-term improved appearance. Automotive Class A surface is attainable with pultruded parts. Part consolidation and a lock together design of two pultruded parts cut production line time by replacing 22 roll-formed aluminum parts.

The pultrusion process, because of its many benefits, lends itself to a variety of other applications, the most popular being standard structural shapes. From 1/8" rod to 48" wide flat sheet, pultruded components are stocked by manufacturers, distributors and fabricators in all major cities in the United States and throughout the world for corrosion, electrical and construction applications.

In conclusion, although the pultrusion process is almost 40 years old, it is still basically in its infancy. New products and processing techniques are being developed every day. Carbon and thermoplastic fibers and cloths provide an even wider range of properties to the pultruded product line for custom applications.

New thermosetting resins and pultrudable phenolic and the work currently being done in thermoplastic resins offer a potential for an unlimited combination of fibers and resin matrices. The pultrusion industry has been growing steadily and new ideas and process development are making pultruded products the system of choice for many current and potential applications.

ACKNOWLEDGMENT

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THE USE OF UNCOATED ALUMINUM AS THE MAJOR COMPONENT OF AMERICAN AIRLINES AIRCRAFT

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Abstract

The author presents the history of American Airlines flying and maintaining basically uncoated airplanes, the types of materials used that do not require coating, why and how these materials were selected, manufacturing techniques used to allow them to be used, and their chemical and physical properties. Maintenance practices and procedures will be reviewed and cost implications versus coated surfaces will be compared. Case studies within the airline industry will be discussed along with potential applications to other industries.

BACKGROUND HISTORY OF AMERICAN AIRLINES FLYING UNCOATED AIRCRAFT

American Airlines has always taken pride in flying and maintaining uncoated fleets of aircraft. Today I would like to share with all of you how this has been accomplished over the years.

Dating back to the very early thirties, American Airlines has flown basically uncoated airplanes. What decorative trim, identification markings and logos on the aircraft were decals. Originally the aircraft were not painted because it was American Airlines Corporate image. Today, however, not only is it our Corporate image but also one of enhanced inspectability, costs associated with paint stripping, waste disposal, primers/paints, and masking materials. Also, weight savings is an important consideration. With today's aging aircraft and environmental problems, it is to our advantage to fly and maintain unpainted aircraft.

Originally on single engine and tri-motor aircraft the exterior skins were made from corrugated galvanized steel. Over the years these galvanized skins were replaced with aluminum. American

The Use of Uncoated Aluminum as the Major Component of American Airlines Aircraft

Airlines took delivery of its first DC-2 in 1934. This aircraft had aluminum skins which were not painted but maintained externally by polishing. In 1936 American Airlines took delivery of DC-3 aircraft, also with aluminum skins maintained externally by polishing. DC-4's were added in 1946 and DC-6 aircraft in 1947. The first aircraft in American's fleet with non-stop coast to coast service was the DC-7. This plane was placed in service in November of 1953. The first jet-powered aircraft to enter American's fleet was the 707 in January of 1959. 707's were followed by the Convair 990 March of 1962 and the 727 in April of 1964. American inaugurated its first 747 jumbojet wide body service in March of 1970 followed by DC-10 wide body service in August of 1971. MD-80, 767 and 757 aircraft have also joined American over the years.

TYPES OF MATERIALS USED IN EARLY YEARS COMPARED WITH TODAY'S

As one can see, American Airlines has been successful over the years in flying and maintaining uncoated aircraft. There are several reasons that can be attributed to this success. One is maintenance practices and procedures, which will be discussed later. The most important, however, is the type of materials used on aircraft since DC-2 aircraft were placed in service. Major commercial jet aircraft are primarily constructed of aluminum. Alclad 2014 was the first alloy used on the fuselage surfaces of older model aircraft. This alloy was eventually replaced by Alclad 2024. It is an aluminum-copper-magnesium alloy that is generally used in the naturally aged temper of T-3. Other alloys used on the exterior of aircraft include Alclad 2219 and Alclad 7075.

WHY AND HOW THESE MATERIALS WERE SELECTED

Throughout this presentation on the various aluminum alloys, the term alclad was used. Alclad is pure aluminum. Alcladding is a process of metallurgically bonding a thin layer of this pure aluminum to the core alloy. The alclad liner is used to improve the corrosion resistance of the core alloy by providing electrochemical protection. The pure aluminum alloy, which has higher electrochemical potential than the core alloy, will serve as a sacrificial anode protecting this inner metal. The alclad can also throw its power of protection over areas that have no alcladding, such as around rivet holes and exposed edges of the metal.

Aluminum alloys are used in commercial aircraft because their weight-to-strength ratios allow construction of an aircraft that can be flown economically. The alloys primarily used in the Aerospace Industry are known as wrought heat-treated aluminum alloys. Wrought alloys are materials that are produced in worked forms such as sheet, foil, plate, extrusions, tubes, forgings, etc. Working operations such as rolling, extruding, and forging combined with thermal practices such as heat treating, annealing, aging, and quenching change the cast ingot structure to wrought structure.

The primary need for aircraft material is to take many types of loads without permanently deforming or breaking. Loads such as gust, shear, acceleration, emergency, etc., must all be designed for. Also the material must withstand cyclic fatiguing and be resistant to corrosion to be used for the primary structure on aircraft.

MANUFACTURING TECHNIQUES THAT ALLOW THESE MATERIALS TO BE USED

The complexity of producing an entire fuselage with aesthetically pleasing and uniform appearance is enormous. Airframe fabrication ranges from severely stretch-formed to substantial chem-milled parts, requiring special mill fabrication. Tailormade practices for the exterior aluminum skins allow for consistent manufacturing results while maintaining an extremely constant finish for the fuselage.

The initial shipment of raw stock utilizes special practices designed to protect the aluminum skins. After the mechanical polishing of the sheets and final inspection, the material is readied for delivery to the airframe manufacturer.

The individual polished panels are separated in their packing container by interleaving of kraft paper and polyester foam. The panels on most aircraft are of various sizes, and extreme caution must be used during packing to ensure the panels do not move during transportation.

Following inspection at the airframe facility the aluminum sheets are coated with a hand-peelable material. This provides surface protection to the polished exterior side of the aluminum sheet. This coating remains on the sheets until removed for painting or final delivery in an unpainted condition.

The fuselage of commercial jetlines is comprised of many different thicknesses and size combinations. The vast number of sizes made it extremely important that the aluminum mills and airframe manufacturers work closely to designate the appropriate aluminum product for the individual fuselage part. The ability to use large panels reduces the need for riveting and minimizes the number of joints.

CHEMICAL AND PHYSICAL PROPERTIES OF THESE MATERIALS

Alloy 2024 has been used for decades because of its strength, high fracture toughness, damage tolerance characteristics and because it retains the damage tolerant characteristics at the -65°F temperatures aircraft fly. Alloy 7075 is a high-strength alloy that is used in areas requiring high strength that do not have the damage-tolerant needs of fuselage skins. These areas include fuselage sections in the rear of the aircraft and on many stringers and frames. Alloy 2219 is used primarily in areas of elevated temperatures such as leading edges where deicing air is located and around engines.

Clad aluminum is very corrosion resistant whereas unclad is not and therefore must be protected by anodizing or another type of protection.

MAINTENANCE PRACTICES AND PROCEDURES

Alclad aluminum is obviously a vital element in protecting aircraft exteriors from corrosion. Another method of corrosion protection is an ongoing washing and polishing program of the exterior alclad skins. Polishing has been accomplished on American Airlines aircraft since the early 1930s. The early model aircraft had what was referred to as commercial mill finish sheets. The skins were polishable but were not the skin quality sheets ALCOA introduced in 1959 on 707 aircraft or the Specul-Air aluminum skins currently used by Boeing and Douglas. The Specul-Air sheet is delivered in a highly polished condition that offers an attractive finish without the expense and environmental problems associated with painted aircraft.

The Use of Uncoated Aluminum as the Major Component of American Airlines Aircraft

American currently washes aircraft in TUL, SAN, JFK, ORD, SJU, MCO, DFW, and DTW. Washing aircraft exteriors is accomplished approximately every 90 days.

Polishing is accomplished only at the Main Base in Tulsa, Oklahoma. The frequency of polishing varies with the aircraft type, but generally it is accomplished every 12 to 15 months.

Polishing aircraft exteriors is not necessarily an easy task nor is it a hard task if certain criteria and requirements are met. Some of these are as follows:

- ◆ *Adequate air pressure to operate several buffers simultaneously.*
- ◆ *Polishing bonnets that are not abrasive enough to scratch or remove alclad.*
- ◆ *Access to the areas to be polished. This access can be in the form of scaffolding, manlifts, scissors lifts and space stacks.*
- ◆ *A buffer that is versatile enough to polish inaccessible areas such as the crown skin, bottom of horizontal stabilizer, bellies, etc.*

American uses a rotary drum buffer commonly referred to as an Astro-Buffer. This apparatus weighs approximately 10 pounds. The pneumatically driven motor develops 0.9 peak horse power at approximately 1500 rpm with 90 psi at the buffer inlet. The rotary drum measures 5 inches in diameter and is 7¼ inches long.

Various attachments are available to allow for polishing of areas as far as 12 feet away.

During the polishing operation an area about 6 x 4 feet is treated. After the polish is applied to the surfaces to be treated, it is buffed at a speed of approximately 1500 rpm and gone over again at speeds between 800 and 1200 rpm to achieve the best finish.

A polish referred to as Perfect is currently in use for polishing American Airlines aircraft. This material replaced the product Alumin-Nu, which had been used since the early 1930s. Use of Perfect Polish results in a shinier more uniform finish and requires fewer man-hours to achieve the desired results. Perfect Polish is a blend of natural materials that cleans, polishes, and protects aluminum surfaces. It is nonflammable, nontoxic and has a neutral pH. Perfect Polish contains no waxes or silicones which for various reasons are undesirable to use on aircraft exterior surfaces.

COMPARISON OF ENVIRONMENTAL/COST IMPLICATIONS OF PAINTED VERSUS NONPAINTED AIRCRAFT

Table 1 summarizes a cost analysis of maintaining a painted aircraft versus a bare polished aircraft. The information was gathered from several airlines in the United States. Each individual airline should address its own value placed on the importance of fuel savings/weight cost and their logos or color schemes.

The paint and stripping costs involved in this table include only the decorative color schemes and not any areas painted for corrosion or composite protection that must be protected at all times.

The area considered is a full white top and bottom with three colors and a complete tail paint scheme.

CASE STUDIES

American Airlines has always been recognized for flying unpainted airplanes. Within the past decade we have been joined by others. U.S. Air and Atlantic Southeast Airlines currently fly and successfully maintain unpainted airplanes. Other airlines to fly and successfully maintain unpainted airplanes were Western and Eastern. Both, however, were unsuccessful in their attempts to continue to fly and maintain unpainted airplanes. Not because the unpainted concept was bad, but other circumstances were encountered. In the case of Western, they were acquired by Delta and Delta elected to convert the Western airplanes to their colors. Eastern at the time of its bankruptcy was flying unpainted airplanes. It can be assumed that both of these carriers would still be flying unpainted aircraft if it were not for their particular situations.

POTENTIAL APPLICATIONS TO OTHER INDUSTRIES

The Specul-Air aluminum skins used on modern day jet aircraft are very expensive. Therefore use of this type material in the Ground Transportation Industry would be prohibitive. However, aluminum alloys, such as the 5000 series, do have corrosion resistance characteristics that would not require paint systems in many applications.

More widespread use of aluminum in the construction industry would be a viable alternative to other types of construction metals. Anodized aluminum comes in a wide variety of colors and is readily available in today's market place. Anodized aluminum is very corrosion resistant and does not require painting.

CONCLUSION

There are a lot of pros and cons about flying and maintaining unpainted versus painted aircraft, but for American Airlines it is flying well-maintained aircraft that takes on immaculate, shining appearance that reminds one of quality and excellence.

ACKNOWLEDGMENT

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TABLE 1. MAINTENANCE COST OF A DECORATIVE PAINT SCHEME
(Standard Three Color, White Painted Fuselage, Full Tail Paint)

AIRCRAFT	747	DC-10	767	757	727/737/ MD80
Weight of Decorative Paint in Pounds	240	165	135	132	110
Repaint Frequency In Years (Average)	5	5	5	5	5
Sand & Overcoat Manhours Airline Cost \$30.00/hour	1,200 36,000	900 27,000	600 18,500	525 15,750	450 13,500
Strip & Repaint Manhours (10 Years) Airline Cost \$30.00/hour	1,600 48,000	1,100 33,000	1,000 30,000	900 27,000	780 23,400
Paint Stripper/Clean Up Solvent Gallons	1,000	700	400	400	300
Cost of Stripper and Disposal Cost (\$40.00/Gallon)	40,000	28,000	16,000	16,000	12,000
Masking/Other Material Cost	3,000	2,600	1,200	1,000	1,400
White Top and Bottom Gallons \$37.50/Gallon	50 *Elec 70 **PP	36 Elec 45 PP	22 Elec 27 PP	20 Elec 23 PP	16 Elec 19 PP
Decorative Colors Gallons \$42.50/Gallon	10	6	5	4	4
Primer Gallons \$21.00/Gallon	20 *Elec 28 **PP	15 Elec 18 PP	9 Elec 11 PP	8 Elec 10 PP	7 Elec 8 PP
Total Cost Sand and Repaint	42,180	31,732	20,522	17,980	15,880
Total Cost Chemical Strip and Repaint	94,180	65,732	48,522	45,225	37,778
Polishing Manhours (Aluminum)	500	450	350	310	150
Polish Maintenance Interval (Times/Year)	1	1	1	1	1
Yearly Polish Aluminum Cost \$18.00/Hour	9,000	8,100	6,300	5,580	2,700

*Elec Electrostatic

**PP Pressure Pot

UNCOATED TITANIUM -- COMPATIBLE WITH THE ENVIRONMENT

Author

Edward E. Mild
TIMET

INTRODUCTION

The recognition by the EPA of the deleterious effects of volatile organic compounds (VOCs) on both the environment and its inhabitants is an important step forward. This awareness has generated a unique opportunity for the development of creative solutions to material degradation problems commonly solved by using coatings containing these VOCs. Coatings containing VOCs have been used to retard the degradation effects of sun, rain, wind, mist, humidity, water (including seawater), soil, and other environmental pollutants. In various forms, organic compounds have been used for hundreds of years to retard atmospheric degradation because they are inexpensive and compatible with most materials of construction. Reducing emissions from VOCs can be accomplished by reducing their use, using less-polluting alternative coating materials, or using alternative materials that do not require coatings of any kind for protection. The coatings industry is working on the first two options and the materials industry is promoting the third. Stainless steels, aluminum, nickel, copper, and titanium all have attractive degradation resistance properties that will help to reduce the amount of VOCs released into the atmosphere. Each of these metals has its own niche in which it will work best. Uncoated titanium metal provides a maintenance-free and highly reliable construction material that can and has replaced many coated materials in applications in which long-term reliability is critical. The increased use of uncoated titanium, in place of materials that require VOC-containing coatings for protection from degradation, is a simple life-cycle-cost-effective solution to the increasing pollution problems caused by VOCs.

WHAT IS TITANIUM?

Titanium is the generic name given to the group of alloys and commercially pure metal of the 22nd element in the periodic chart. Titanium is the fourth most abundant structural metal and the ninth most abundant element in the earth's crust (Table 1). Its mineable ores are found all over the world (Figure 1), which allows the raw material to remain accessible and geopolitically stable. The metal-producing industry, which consumes less than 10 percent of the ore that is mined annually, primarily uses the ore dredged from the western beach sands of Australia. The pigment industry, which uses over 90 percent of the mined ore, gets its supply from Australia and the rest of the world, including Canada, South Africa, and Sri Lanka.

Titanium is a gray-colored metal with a density about half that of steel and nickel and slightly more than double that of aluminum. The yield strength of the family of titanium alloys varies from about 25,000 psi, which is roughly the strength of mild steel, to over 200,000 psi, which corresponds roughly to that of high-strength steel. Tables 2 and 3 present physical and mechanical properties of several titanium alloys and compare them with steel and aluminum. However, respectively, the property of titanium that separates it from the other common construction metals is its corrosion resistance in many environments, including the effects of erosion and corrosion in all naturally occurring waters. Titanium is immune to the erosion and corrosion effects of both still and flowing water. This lightweight, strong, corrosion-resistant metal, has been used for nearly 40 years in jet engines and jet airframes to allow these planes to perform as they were designed. Jet air travel would not be possible without titanium, because steel is too heavy and aluminum melts at too low a temperature to work satisfactorily.

Titanium is won from its ores through a multistage process (Figure 2). The process begins with the chlorination of the ore to titanium tetrachloride, which can be used to make either pigment or metal depending on the next step in the process. In the manufacture of pigment, the tetrachloride is oxidized to titanium dioxide, which is the brilliant white opaque matter in paint and plastics. In the manufacture of metal, the tetrachloride is combined with either liquid sodium or liquid magnesium under vacuum or argon pressure to produce titanium metal (called sponge at this point) and either sodium or magnesium chloride. The salt is removed from the titanium metal and recycled back into the process to generate chlorine and sodium or magnesium, each of which is recycled back into the process; chlorine is combined with the ore to make the tetrachloride, and sodium or magnesium is again reacted with the tetrachloride to make titanium sponge and salt. The titanium sponge is then mixed with alloying elements, if necessary, and then melted under vacuum or argon pressure and solidified into ingot form. These ingots are then processed into all of the common mill product forms in which metals of construction are found (Table 4).

THE TITANIUM INDUSTRY

The titanium industry was born in 1950 based on a process developed by Dr. Wilhelm Kroll in the 40's to manufacture the sponge commercially. TIMET and MALLORY SHARON TITANIUM (now RMI TITANIUM) were incorporated in that year in the USA. The rest of the world industry (Table 5) evolved from that core of companies. About 52 percent of the world titanium industry is located in non-Communist countries and 48 percent is located in the USSR and China (Figure 3). In the United States, TIMET, RMI TITANIUM, and OREMET are the only integrated producers, i.e., they manufacture sponge, ingots, and mill products. All other producers buy sponge, ingot, or intermediate mill product and convert them to mill products. Although titanium is not as ubiquitous as steel or aluminum, it now can be bought off-the-shelf in all of its product forms from numerous warehouses and service centers.

The current free-world titanium industry capacity is about 126 million pounds (52,000 tons) of sponge and 196 million pounds (98,000 tons) of ingot melting compared to a current demand

of about 65 million pounds (33,000 tons) of mill product demand. This indicates that there is plenty of industry capacity to support the growth of new applications. The goal of the U.S. industry is to double in size by the year 2010 and the infrastructure has been put in place to support this growth. The anticipated growth will occur in applications that utilize titanium's corrosion and erosion resistance. Currently, only about 25 percent of the entire consumption of titanium mill products goes to non-aerospace applications for which resistance to environmental degradation is the driving force for titanium's use.

WHY IS TITANIUM CORROSION RESISTANT?

Titanium's corrosion resistance is based on the formation of an extremely tenacious and stable surface oxide film that is illustrated in Figure 4. This oxide layer, which forms instantaneously when a fresh surface is exposed to air or moisture, is only 12 to 15 one hundred millionths of a centimeter thick. This film continues to grow slowly in air until it reaches about 250 one-hundred-millionths of a centimeter in thickness in 4 years. When the surface of titanium is scratched, the film heals itself instantly in any environment containing even a trace of oxygen or moisture. However, the film will not regenerate itself when damaged in anhydrous conditions in the absence of oxygen. Only a few substances, such as hot, concentrated hydrochloric acid, sulfuric acid sodium hydroxide and, most notably, hydrofluoric acid, attack this stable oxide film.

Titanium is immune to a long list of environments as shown in Table 6. Titanium's corrosion resistance is extended in many environments in which heavy metal ions are present. This allows titanium to be used, for example, in hydrochloric acid in which iron copper or chromium ions are present. These corrosion resistance properties of titanium make it ideal for use in many chemical and petrochemical processing applications.

USES FOR UNCOATED TITANIUM

Applications for uncoated titanium exist in many areas. Its use is a function of its ability to withstand environmental degradation, which precludes the use of alternative materials or coatings. We will discuss three main applications areas: architecture, power plant flue gas desulfurization systems, and seawater applications.

Architecture: Why would anyone want to use titanium in architectural applications? The answer is that in coastal construction, titanium withstands the degradation effects of the sea spray and salt water environment in addition to having the necessary strength and fabricability to be used as a siding or roofing material. Other metals such as aluminum and stainless steel have been used in roofing, siding, window frames, and doors for many years. However, in sea coastal areas these applications require frequent maintenance and replacement due to the corrosive nature of the salt water environment. Although titanium has not been used in the United States for architectural applications, it has been used extensively in Japan to reduce the degradation effects of sea mist. Titanium has been used successfully in Japanese coastal cities in many architectural applications to eliminate the deleterious effects of the environment. Figures 5 through 8 show typical titanium applications in Japanese architecture. From an esthetic

perspective, titanium can be used in its natural metallic gray color or it can be anodized to hues of red, blue, gold, or purple to provide a variety of decorative appearances. Although the cost of titanium in these applications is greater than the cost of stainless steel, titanium is preferred because maintenance and replacement are reduced. On a 40-year life-cycle cost basis, the full cost of titanium changes to roughly half that of stainless steel based on reduced maintenance and no replacement of the titanium.

Power plant flue gas desulfurization (FGD) systems: FGD systems are used to remove sulfur dioxide and other harmful stack emissions from power plants. The gases produced from the burning of fossil fuels are scrubbed in the FGD system to remove sulfur dioxide, which produces acid rain. The use of metallic linings in these flue gas desulfurizing systems is a major step toward decreasing maintenance and increasing the operating time of these air pollution (acid rain) reducing units. Ceramics, glass block, and organic linings were originally installed prior to the use of metal linings in this application. As shown in Figures 9 and 10, nickel-based alloys and stainless steels, which were used after the nonmetallic, were found to be lacking in long-term corrosion resistance to the aggressive environment of the gaseous effluent stream. Titanium's use in the outlet ducts and stacks of FGD systems has replaced the nickel-based alloys and stainless steels. Uncoated titanium is used based on its corrosion resistance against gaseous effluents, in particular hot acidic chlorides and sulfate species, which are by-products of sulfur dioxide removal from the gases produced from the burning of high-sulfur-containing fossil fuels (coal and oil). In addition to its corrosion resistance, titanium is preferred in these field-installed applications because of its low density (half that of steel or nickel-based alloys) and its ease of fabrication and welding. Currently, 110 power plants, mostly in the Midwest, have been identified by the Federal Government as requiring new or improved FGD systems. Uncoated metals, in particular titanium, will be used as a lining material in the great majority of these units because of the severity of the corrosive gases passing through these systems.

Seawater applications: By far the largest potential for the use of uncoated titanium is in applications in which titanium's resistance to seawater corrosion and erosion is of prime importance. Titanium's other engineering properties are also used to advantage in these corrosion-susceptible applications.

Heat exchangers and power plant main steam condensers cooled by seawater are the largest of the current seawater applications. Figure 11 shows the tube bundle of a power plant main steam condenser being welded. This 100-foot condenser is made of welded titanium tubes, a titanium tube sheet, and titanium spacers. Typical heat exchangers used in a chemical or petrochemical plant are shown in Figure 12. Titanium heat exchangers and condensers utilize the corrosion and erosion resistance of titanium by increasing seawater flow rates through or around the tubing in order to optimize heat dissipation. The reduced weight of titanium heat exchangers is an added advantage when they are used on offshore oil and gas exploration and production platforms because a reduction in equipment weight will allow lighter supporting structures to be built, reducing the buoyancy requirements.

Seawater piping systems of titanium including pipe, valves, pumps, and fittings (Figures 13 through 15), are commonly used in chemical and petrochemical processing plants. These systems use uncoated titanium except where color is used to designate the type of system. Any piping system that transports seawater or brackish water should be made of titanium because of titanium's corrosion and erosion resistance and because exterior painting is unnecessary.

Oil and gas well piping, transmission lines, and riser systems are currently evaluating the use of titanium because of its mechanical properties as well as its corrosion resistance. Although coatings will still be used initially, the potential for eliminating these coatings is real. The coatings will be used not because they are necessary but because they have always been used on the steel that titanium will replace, and one change at a time is all that the conservative oil and gas industry is willing to make.

There are numerous other current and potential applications for uncoated titanium in seawater. Some of these include tether anchors and ballast water systems used on offshore oil production and drilling platforms; heat exchangers and natural gas coolers for use on offshore platforms; sheathing for steel pilings to protect against corrosion and erosion at the seawater surface and the spray zone just above the surface; hulls for submersibles and surface ships; propulsion pumps and shafts for hydrofoils and other vessels; and exhaust stacks and structures on merchant and military ships. Although each of these applications has its own distinct requirements for mechanical and physical properties, each utilizes to its advantage the corrosion-resistant nature of the titanium surface, which needs no coating to protect it from the ravages of seawater.

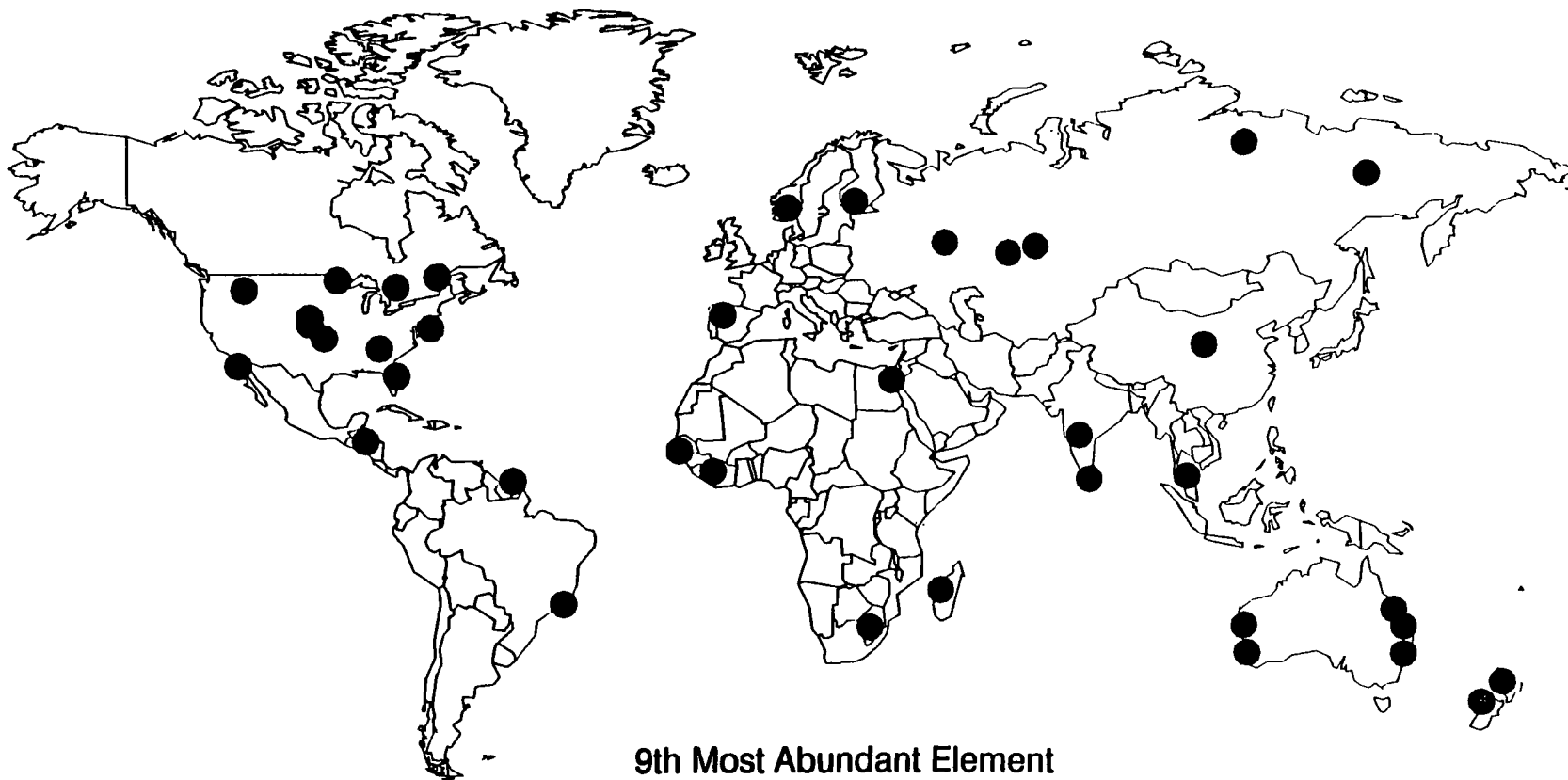
SUMMARY

The EPA's goal of the reduction of volatile organic compounds released into the environment can be accomplished through the use of uncoated titanium. Because titanium is resistant to degradation by any naturally occurring water, soil, typical atmospheric species, or atmospheric pollution, it can be used as a material of construction in applications where coatings are needed to prevent corrosion or degradation on less stable materials. Titanium can be used in its natural gray metallic color or it can be anodized to various decorative colors. Whether in architecture, seawater, industrial gas effluent cleaning systems, or in other service where corrosion resistance is of importance, titanium, the youngest of the industrial metals, can and is being used effectively. Its use on a wider basis should be explored and promoted by the Environmental Protection Agency as one of their programs aimed at reducing the release of VOCs into the atmosphere.

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MAJOR TITANIUM ORE DEPOSITS



9th Most Abundant Element

4th Most Abundant Metal

Source: DoD MCIC 1981.

FIGURE 1. MINEABLE TITANIUM ORE DEPOSITS

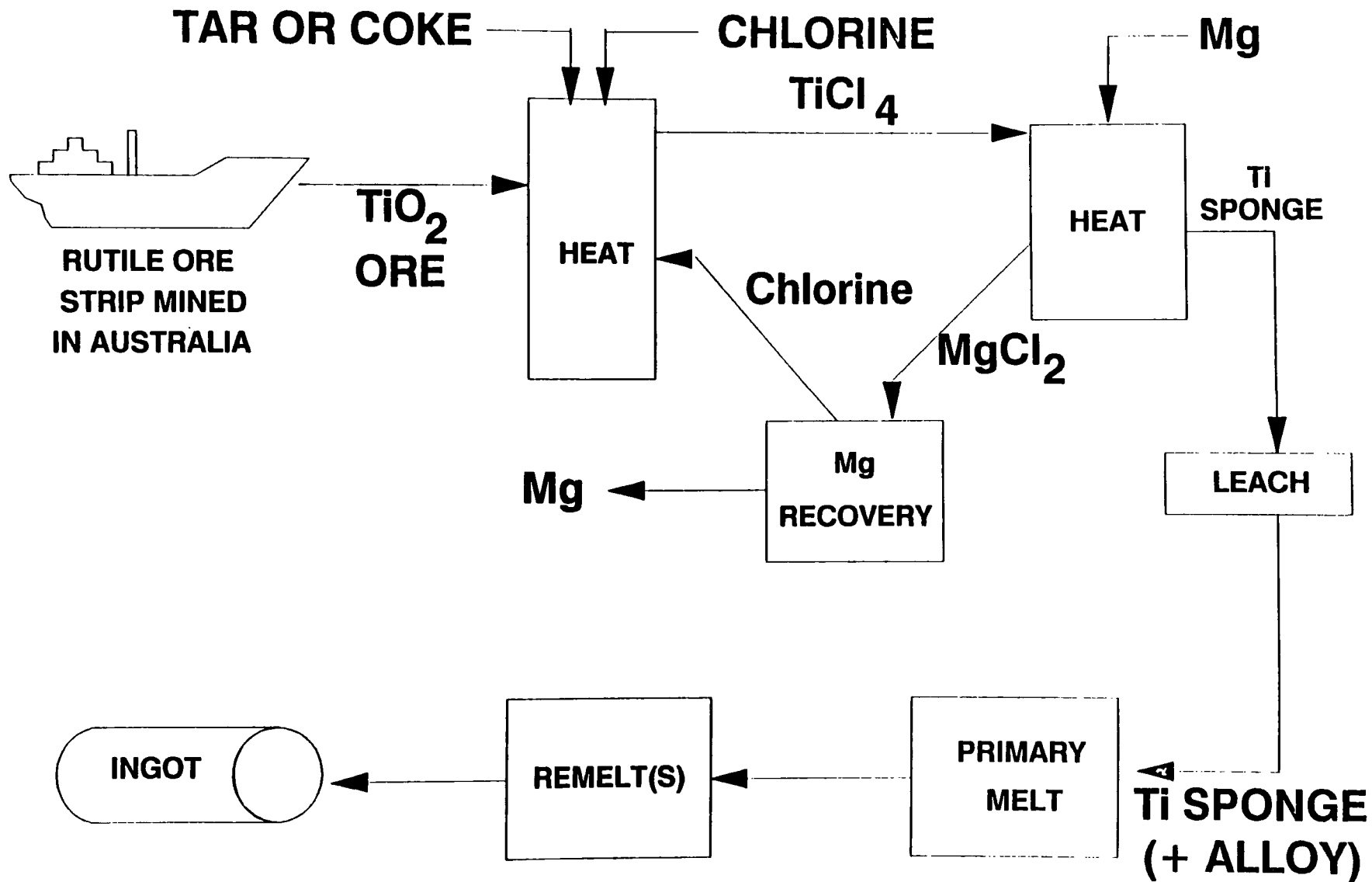


FIGURE 2. SCHEMATIC OF TITANIUM WINNING PROCESS

WORLD TITANIUM SHIPMENTS MILL PRODUCTS

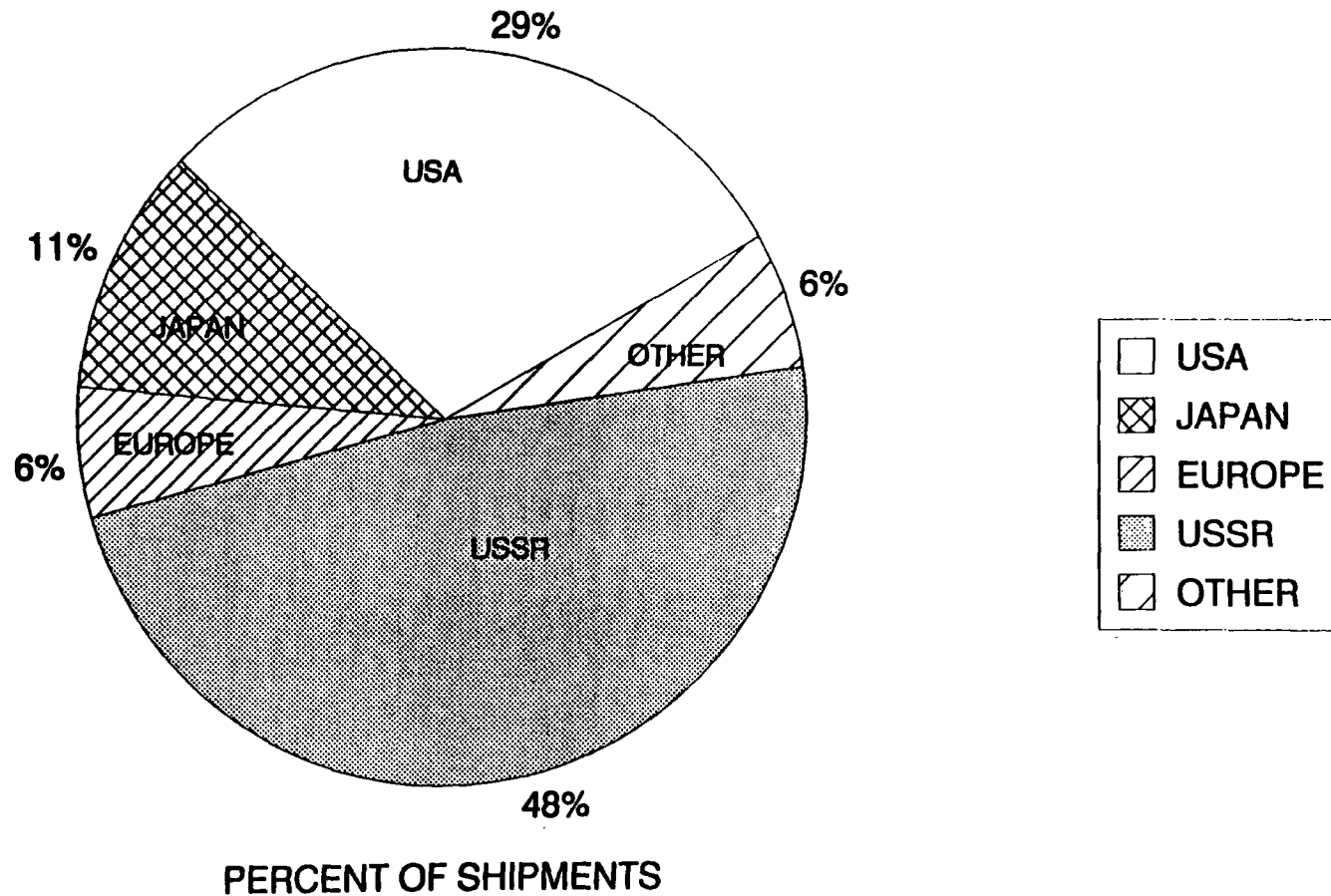


FIGURE 3. DISTRIBUTION OF WORLD TITANIUM SHIPMENTS

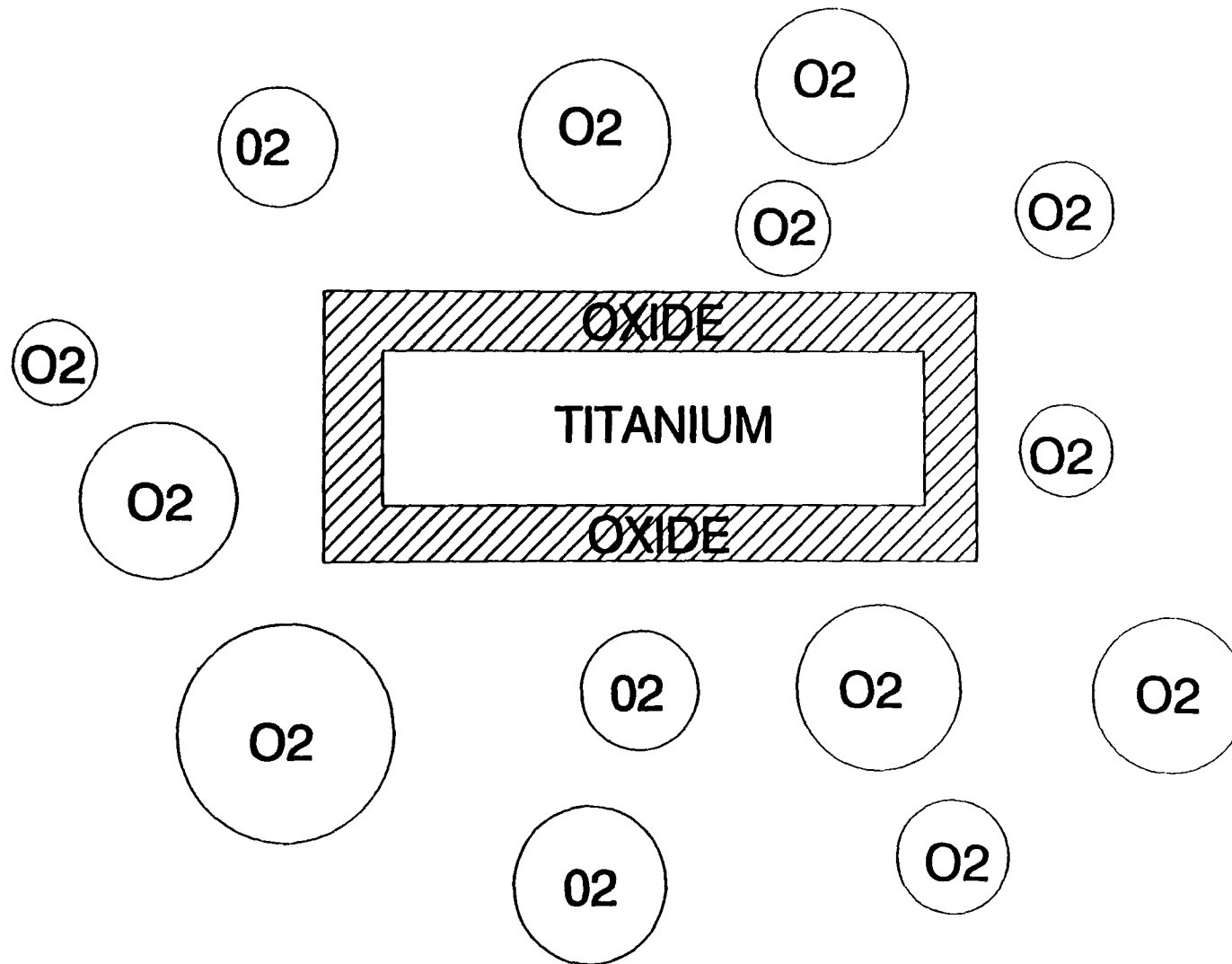


FIGURE 4. SCHEMATIC OF OXIDE FILM ON TITANIUM SURFACE

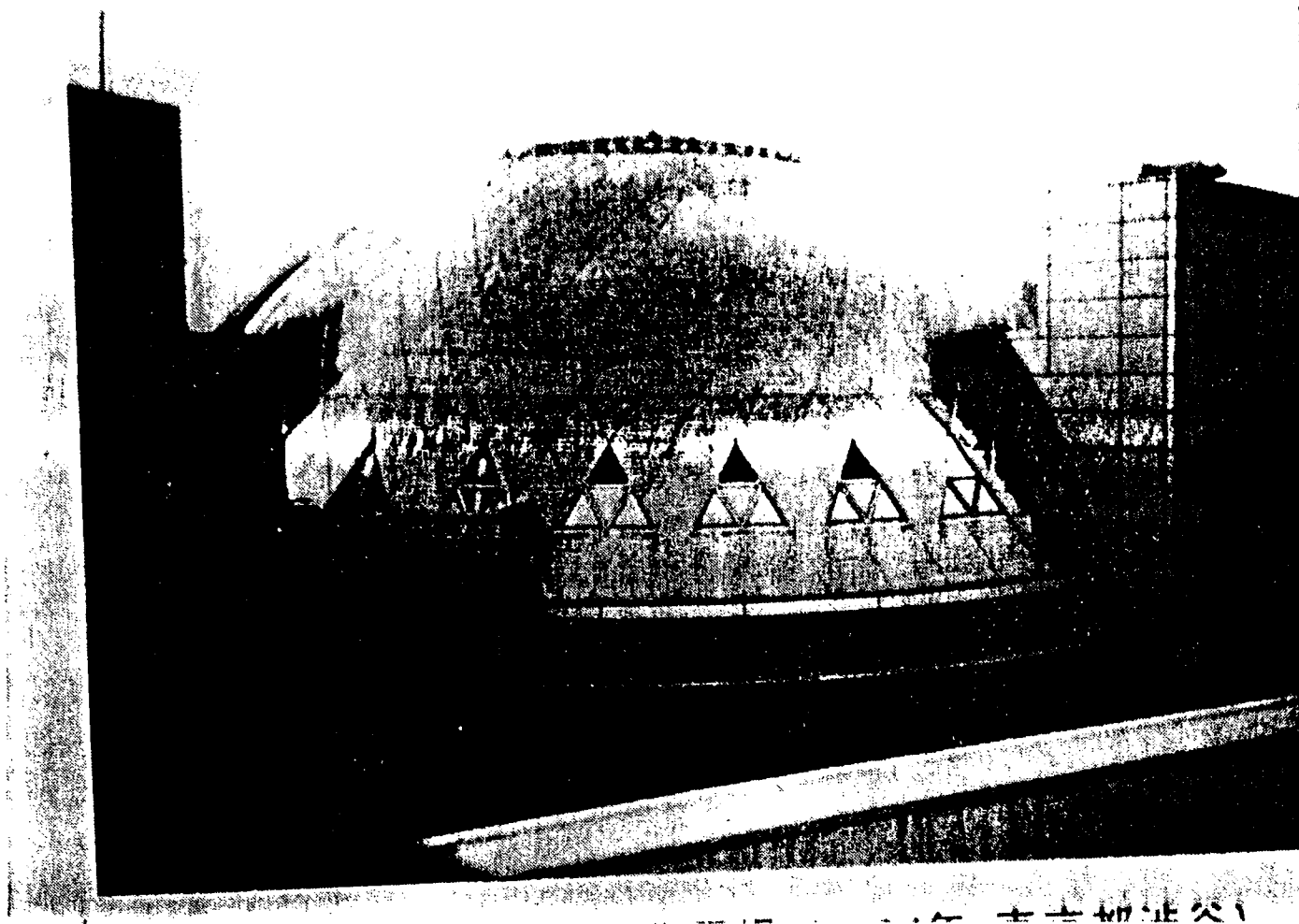


FIGURE 5. TITANIUM DOME ROOF ERECTED IN JAPAN

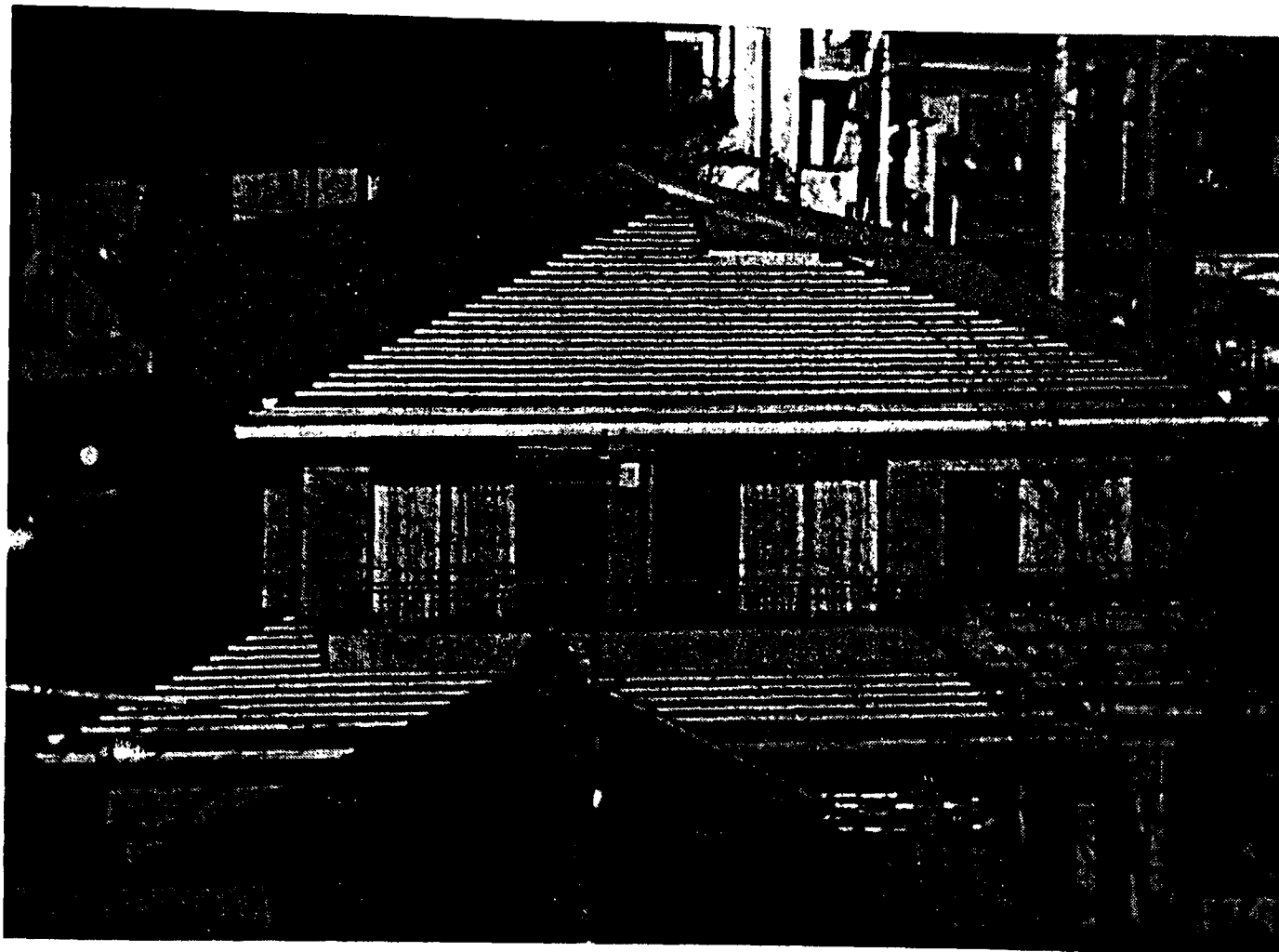
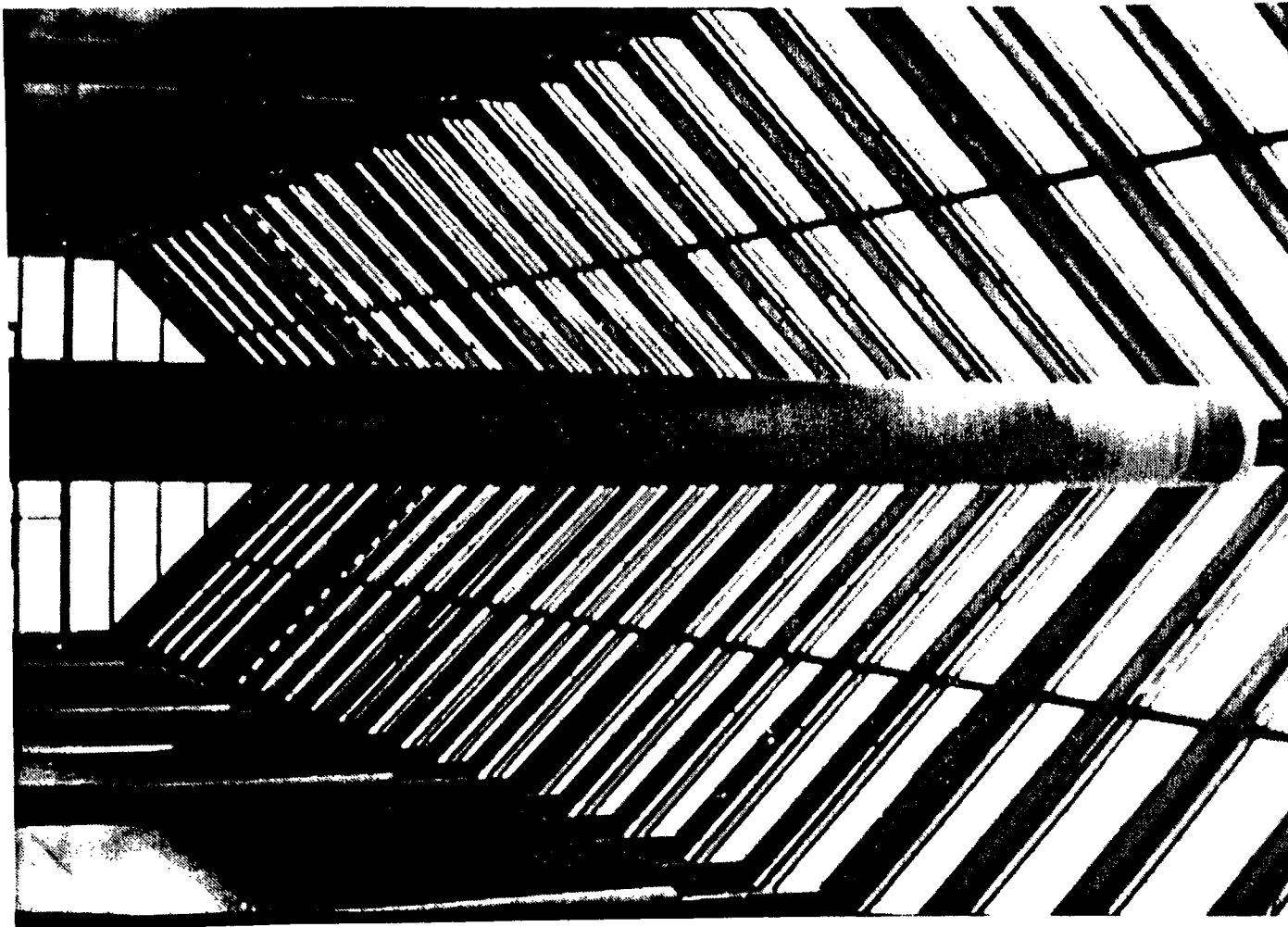


FIGURE 6. TITANIUM RESIDENTIAL ROOF IN JAPAN



**FIGURE 7. ANODIZED TITANIUM USED FOR INTERIOR
DECORATIVE TRIM IN JAPANESE OFFICE BUILDING**



FIGURE 8. TITANIUM CURTAIN WALL SIDING ON A JAPANESE OFFICE BUILDING

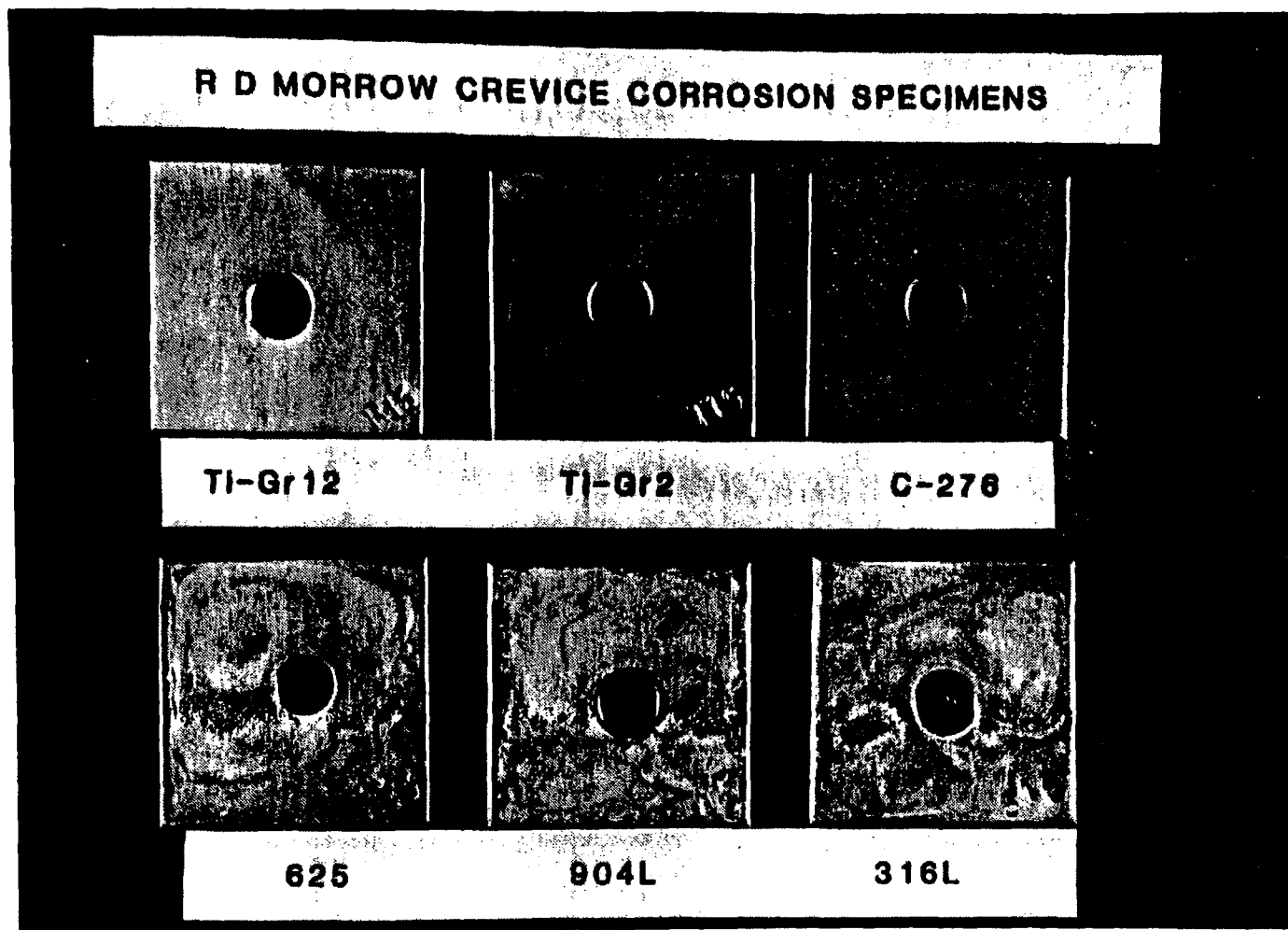
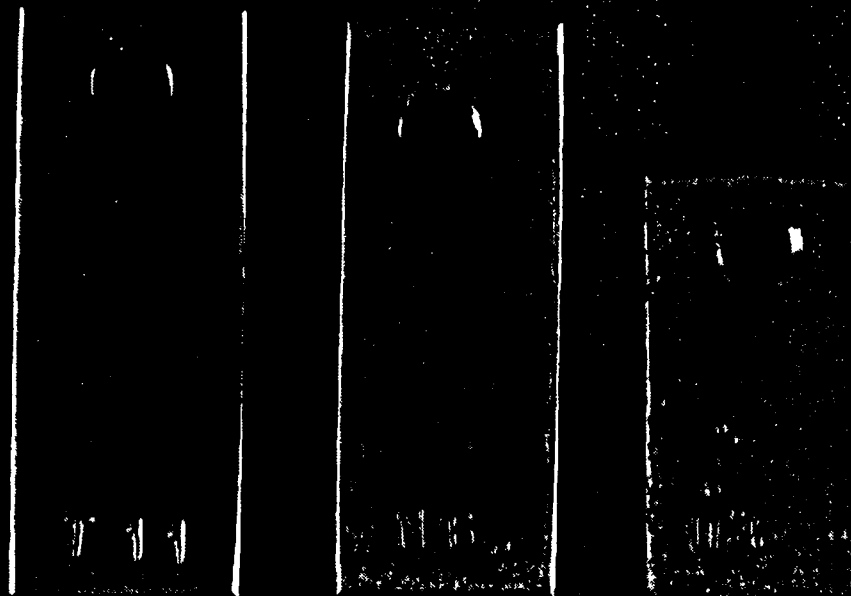


FIGURE 9. CORROSION TEST SAMPLES TAKEN FROM THE STACK OF AN OPERATING FDG SYSTEM

IMMERSION PITTING SPECIMENS

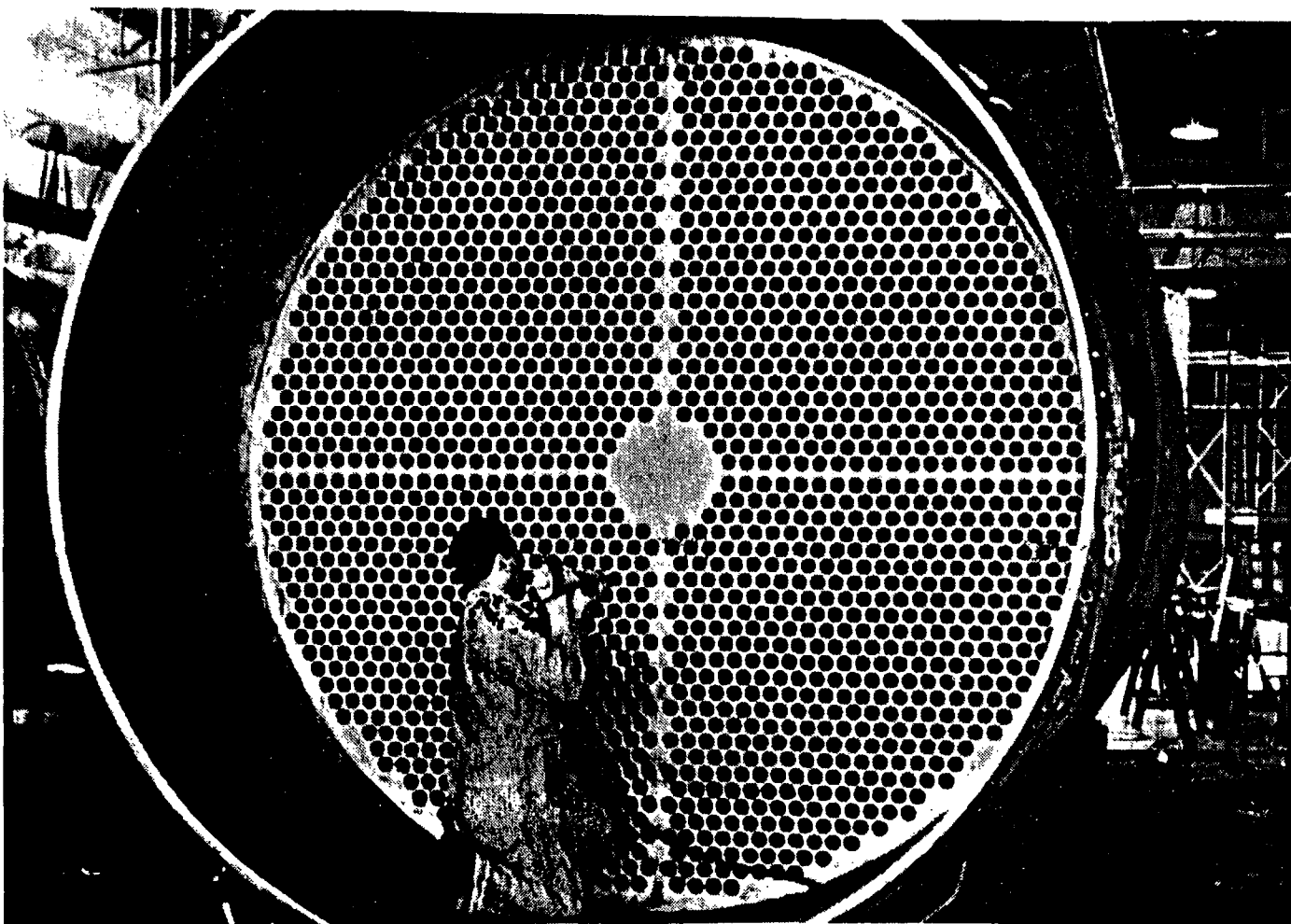


TI-Gr2

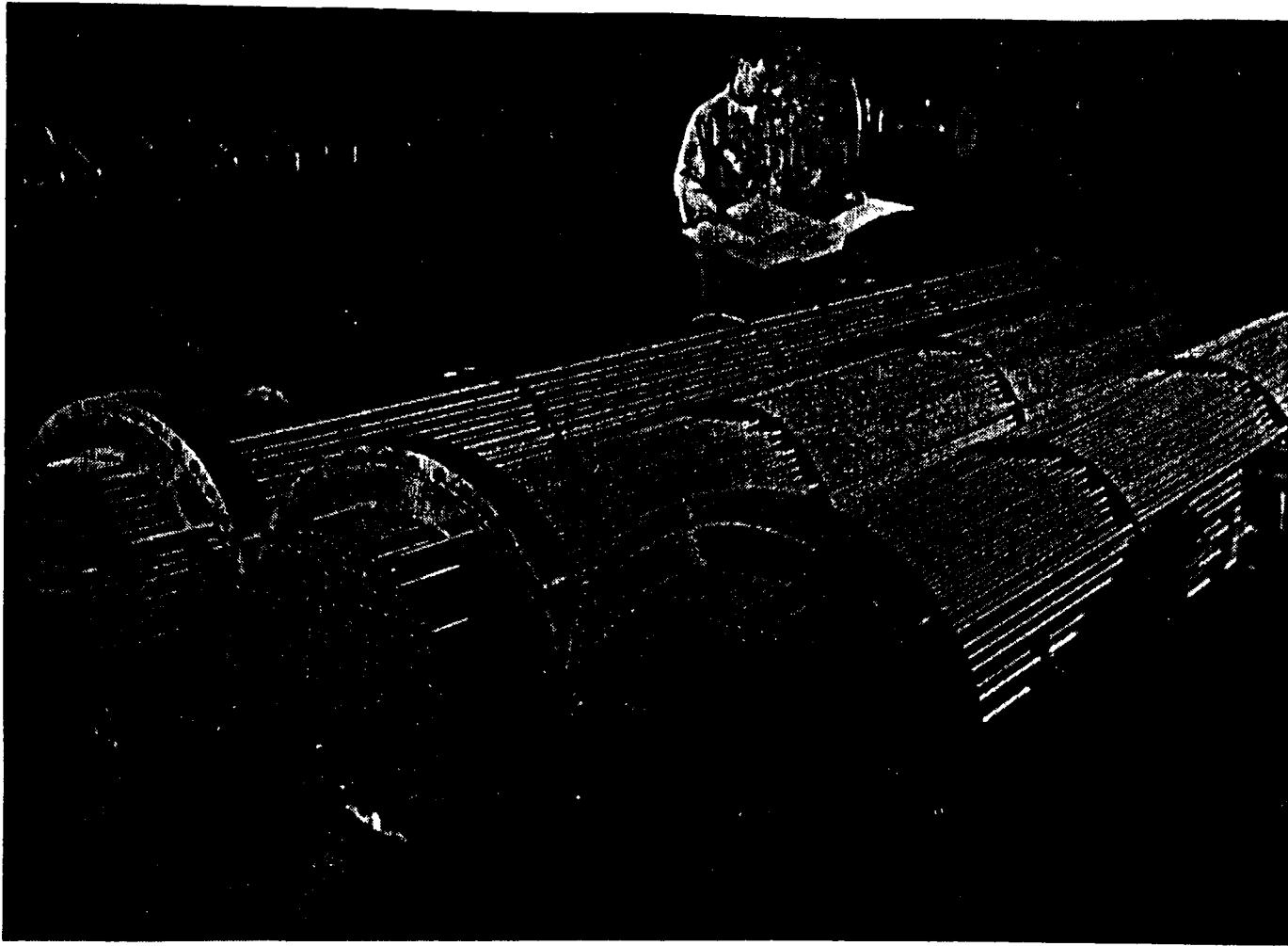
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**FIGURE 10. CORROSION TEST SAMPLES TAKEN FROM
THE OUTLET DUCT OF AN OPERATING FGD SYSTEM**



**FIGURE 11. POWER PLANT MAIN STEAM CONDENSER
WITH TITANIUM TUBES AND TUBESHEET**



**FIGURE 12. TYPICAL TITANIUM HEAT EXCHANGER BUNDLE
USED IN THE CHEMICAL PROCESSING INDUSTRY**

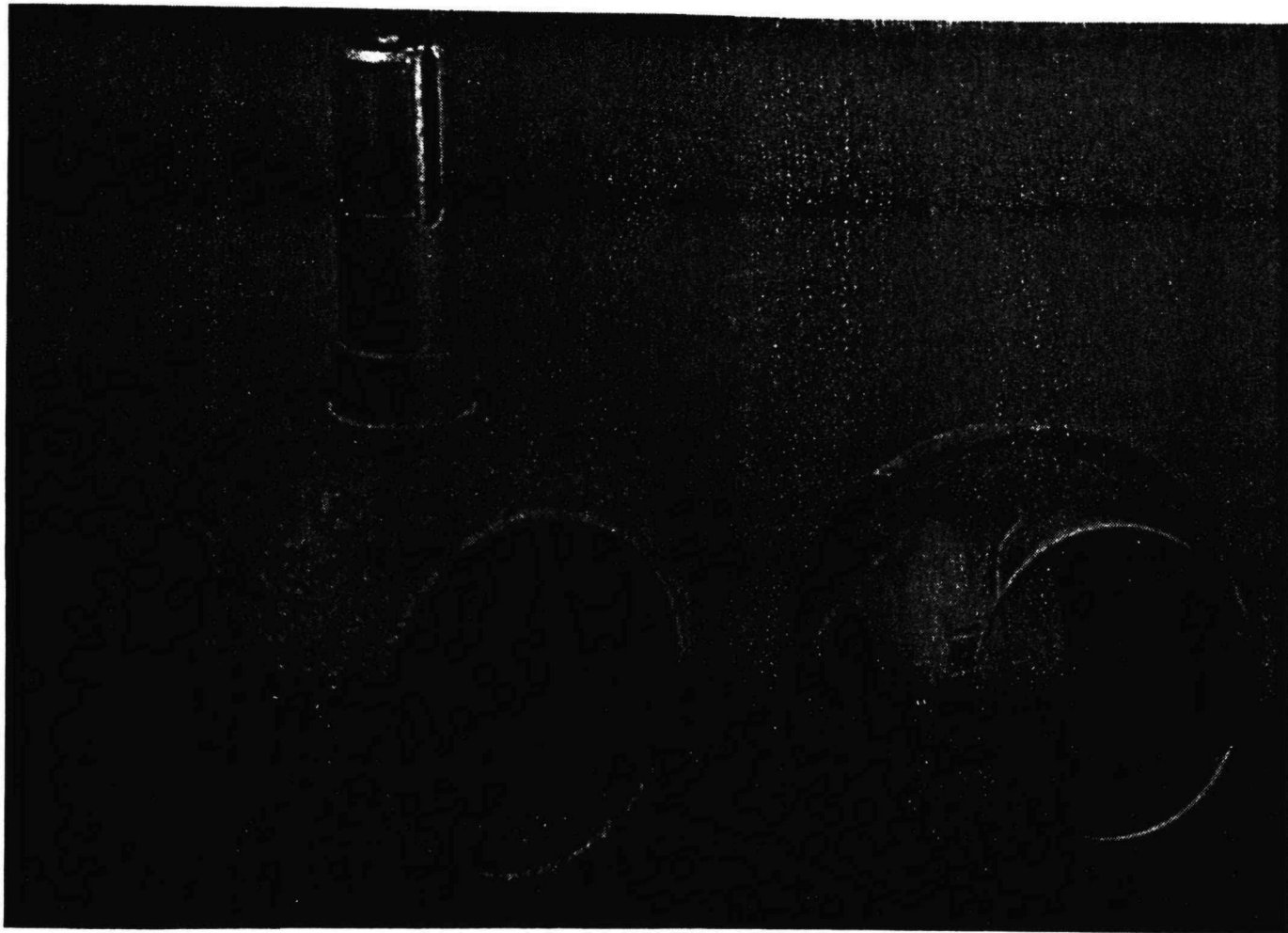


FIGURE 13. TITANIUM BALL USED IN A SEAWATER BALL VALVE COMPARED TO A CORRODED STAINLESS BALL

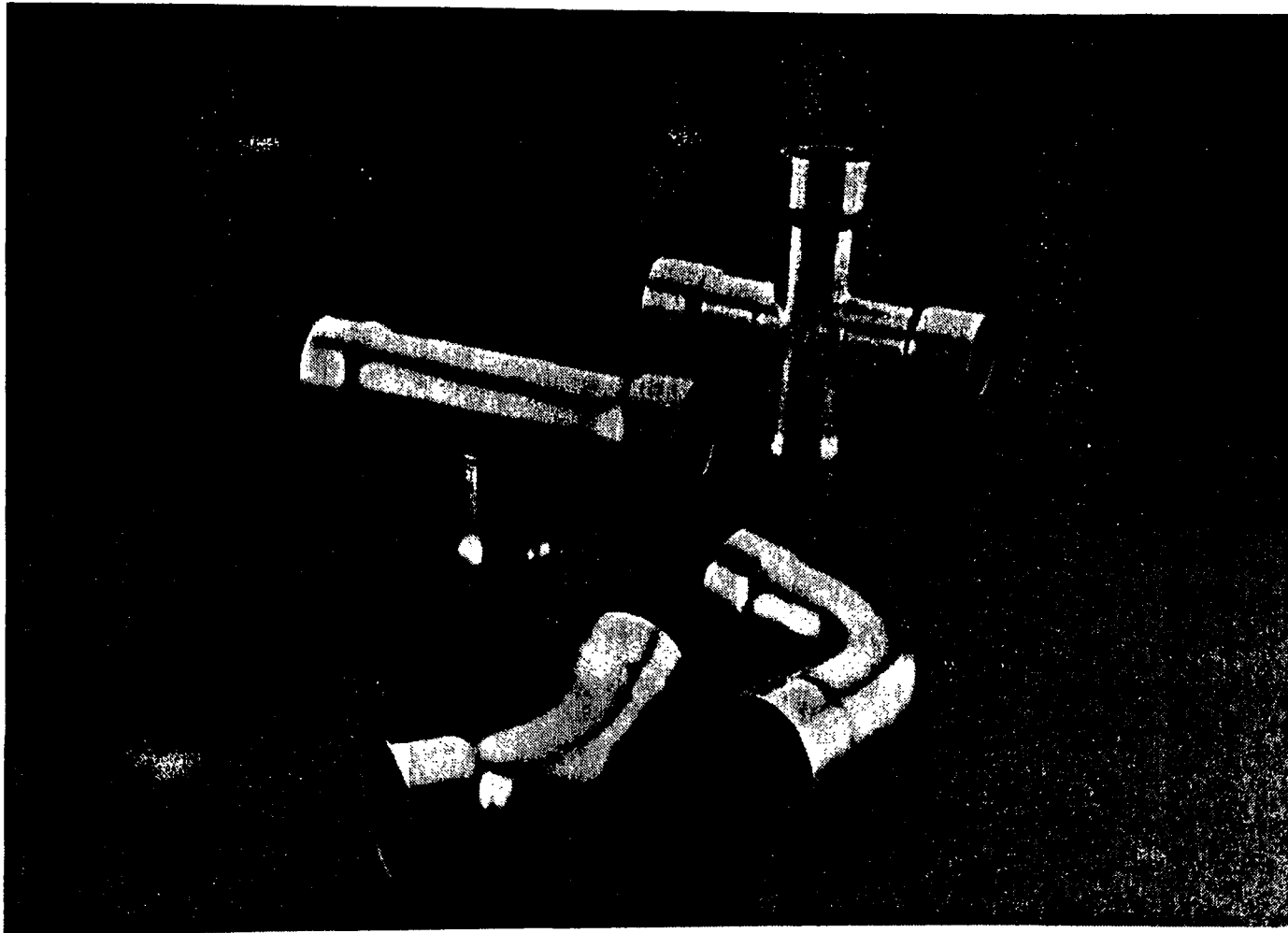


FIGURE 14. TYPICAL TITANIUM TUBING FITTINGS

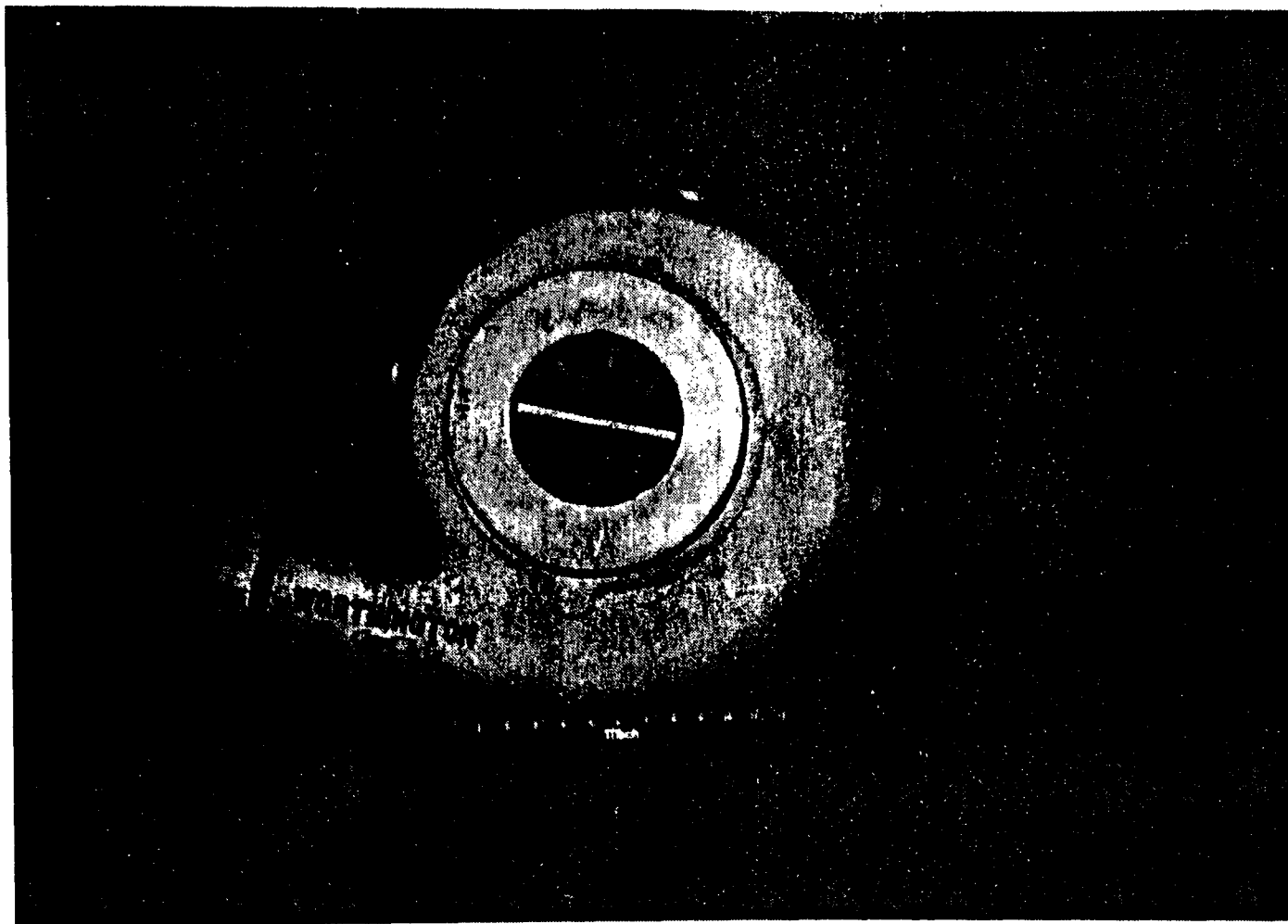


FIGURE 15. TITANIUM 1000 GALLON PER MINUTE SEAWATER PUMP FOR NAVY SURFACE SHIPS

TABLE 1

**AVERAGE AMOUNTS OF THE ELEMENTS
IN THE EARTH'S CRUST
In parts per million**

	ELEMENT	QUANTITY
1	Oxygen	466,000
2	Silicon	277,200
3	Aluminum	81,300
4	Iron	50,000
5	Calcium	36,300
6	Sodium	28,300
7	Potassium	25,900
8	Magnesium	20,900
9	Titanium	4,400
10	Hydrogen	1,400

Source: Handbook of Materials Science. 1974.

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TABLE 2
COMPARISON OF PHYSICAL PROPERTIES

	Titanium CP Grade 2	Titanium Ti-6Al-4V ELI	316 Stainless Steel	Aluminum
Density, lb/cu.in.	0.163	0.16	0.29	0.097
El. Modulus, 1000 ksi	14.900	16.50	28.00	10.500
Therm. Exp, in/in/F	4.900E-06	1.01E-05	8.90E-06	1.250E-05
Therm. Cond, BTU/h-ft	9.500	4.20	7.50	79.860

TABLE 3
COMPARISON OF MECHANICAL PROPERTIES

	Titanium	Titanium		
	CP Grade 2	Ti-6Al-4V ELI	316 Stainless Steel	Aluminum
Tensile Str'ngth, ksi	50	130	85	30
Yield Strength, ksi	40	120	30	25
Elongation, %	20	10	50	22
Fract. Tough.,(K1c) (ksi)($\sqrt{\text{in}}$)	60	90	100+	15
Fatigue Limit, ksi	25	60	40	10

TABLE 4 MILL PRODUCTS AVAILABLE

- INGOT**
- BLOOM**
- BILLET**
- SLAB**
- BAR**
- PLATE**
- SHEET**
- STRIP**
- WELDED TUBE/PIPE**
- SEAMLESS TUBE/PIPE**
- WIRE**
- EXTRUSIONS**
- CASTINGS**

TABLE 5

**TITANIUM PRODUCTION CAPACITY
BY REGION
(millions of pounds)**

	SPONGE	VAR MELT	COLD HEARTH MELT
USA	61	132	20
JAPAN	54	45	5
EUROPE	11	19	0
USSR	110	120+	3
PRC	6	8	10
TOTAL	242	324+	30

SOURCE: Titanium Development Association

TABLE 6
TITANIUM CORROSION RATE DATA

	CONCENTRATION, %	TEMPERATURE, F	CORROSION RATE, mpy
Acetic acid	5 to 99.7	255	nil
Benzene	liquid	80	nil
Boric acid	satuated	80	nil
Chlorine gas, wet	1.5% water	392	nil
Ferric chloride	10 to 30	212	<0.5
Magnesium chloride	5 to 20	212	nil
Nitric acid	10	80	0.19
Phosphoric acid	10 to 30	80	0.8 to 2.0
Seawater			nil
Silver nitrate	50	80	nil
Sodium hydroxide	5 to 10	212	<.85
Sulfuric acid	3	140	0.5

UNCOATED WEATHERING STEEL FOR BRIDGES AND OTHER STRUCTURES

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Abstract

Weathering steel is a high-strength steel containing low amounts of chromium and other alloys. Under certain circumstances, these alloys promote the formation of a tightly adhering dense oxide layer (patina) which precludes the need for a surface coating. This property provides distinct advantages over conventional carbon steel, which requires a coating system for corrosion protection in virtually all exterior atmospheric environments.

Questions have been raised regarding the specific conditions under which the patina will form. Chlorides, continuous moisture, and "tunnel-like" configurations have been shown to interfere with the formation of the patina.

Data are presented on case histories of successful uses of unpainted weathering steel, as well as instances in which this material has shown unacceptably high rates of corrosion. Also discussed are circumstances under which portions of a structure may be left uncoated, while the portions subject to the most aggressive conditions (which are often also the most critical elements) are coated. Guidelines are being developed for identifying and selecting conditions and procedures for making the greatest use of unpainted weathering steel while still providing adequate corrosion protection.

INTRODUCTION

The Steel Structures Painting Council (SSPC) is a not-for-profit technical association. The SSPC mission is to develop and promote good practice for corrosion protection of industrial structures primarily through the use of protective coatings. The three major activities of SSPC are to conduct research and development, develop standards, and disseminate information.

The primary means of protecting steel from corrosion is through protective coatings or paint. SSPC is also interested in alternative, coating-free technology, which can help the facility owners (e.g., bridges, power plants, petrochemical plants) achieve cost-effective protection.

Carbon steel is a primary construction material because of its high strength, its favorable fabrication and welding properties, and its relatively low cost compared to alternative structural materials. In most industrial environments, which are subject to moisture, condensation, and even slightly polluted air, carbon steel will react with the environment to form oxides (rust) which flake away and gradually erode the steel. Normally, therefore, carbon steel is painted or coated to provide a barrier between the steel and the environment. Coatings for industrial structural steel do not last indefinitely, and most often structures must be maintained by repainting after 10-20 years.

Accordingly, any technology which can permit the use of steel as a structural material but avoid the need for initial coating and recoating would elicit keen interest among the many industries that utilize steel for construction. Weathering steel, which can meet these criteria, is the subject of this paper.

The topics to be addressed are as follows:

- ◆ *What is Weathering Steel?*
- ◆ *Brief History of Weathering Steel*
- ◆ *Conditions to Achieve and Avoid*
- ◆ *Remedial Maintenance*
- ◆ *Life Cycle and Economics*
- ◆ *Summary of Advantages and Limitations*
- ◆ *Recommendations*

What is Weathering Steel?

Weathering steel is a high-strength, low-alloy steel (HSLA) for structural use. Small amounts of copper, chromium, manganese, and phosphorus are added to give it its special strength and protective properties. Weathering steel, under certain conditions, can form a protective oxide layer on the steel. Unlike the oxide that forms on mild (carbon) steel, which readily hydrates and flakes off as rust, the oxide on weathering steel is tightly adherent and consequently can protect the steel against further reaction with oxygen and moisture. The term "weathering steel" refers to the fact that this protective oxide layer (also known as patina) is formed after the steel has been exposed to the atmosphere (weathered) for a certain length of time.

The major advantage of weathering steel claimed by the manufacturers is the elimination of the need for painting. Painting not only adds to the cost of a bridge or other structure but raises environmental and toxicity concerns because of the ingredients used in the paint and the operations to remove aged and deteriorated paint.

Another way that weathering steel differs from carbon steel is in its appearance. Weathering steel typically has a rough, grainy appearance because of the manner in which the oxide is formed. This involves alternate solubilization and crystallization of oxides and alloys. In addition, the color typically ranges from an orange-brown to a deep, dark almost black brown. Thus, unlike painted bridges, where virtually any color or gloss is attainable, with weathering steel the color and appearance are severely limited.

Brief History of Weathering Steel

Weathering steel is not exactly a new material. The improved corrosion resistance of steels containing copper was noted in the 1800s. The first commercial use of weathering steel was in the 1930s on coal hopper rail cars. More than 1 million cars were constructed of weathering steel, which was considered a very successful use of the product. ASTM issued the first standards on weathering steel in the 1940s. Weathering steel actually consists of several different types of alloys with minimum levels of the alloying elements required.

The alloy development and testing continued in the 1950s and 1960s. In the mid-60s, the steel industry, convinced that this product had extremely wide potential usage, began heavily promoting it for architectural uses (e.g., office buildings, warehouses) and industrial uses (highway bridges, utility towers). The first bridges were erected in 1964 and 1965. Over the next 15 years, over 2,000 such bridges were constructed. The largest users were Michigan (with over 500 structures by 1980), North Carolina, New Jersey Turnpike, and New Hampshire. Electric utility companies such as Virginia Power and New York Power Authority also used weathering steel to construct thousands of utility towers during the same time period.

Thus, the promise of a coating-free structural steel was apparently being realized by two major industries. However, as the bridges and utility towers aged and weathered, it became evident that the formation of the protective oxide and the reduction in corrosion were not always achieved.

In the late 1970s, Michigan DOT engineers noticed continuous heavy scaling and pitting in Detroit's bridges, which were 10 years old. They concluded that these structures would not last their designed lifetime because of the loss of metal, and that critical areas, such as joints, could present structural safety problems. In 1979, Michigan DOT issued a moratorium (i.e., ban) on new weathering steel bridges because of the above-noted corrosion problems.

A major controversy erupted within the steel construction industry, which has not yet been resolved among the varying parties, which included bridge engineers, consultants, and the steel industry. A number of studies were initiated to determine the extent of corrosion, the number of bridges affected, and to determine what, if any, corrective measures were needed. SSPC

became involved as one of the considerations was the painting of weathering steel, both for new construction and for existing structures.

As a result of the research and evaluation studies, a series of conferences, negotiations, and even some court cases, the steel industry accepted the fact that weathering steel was not suitable for many conditions or environments. In addition, the steel was NOT maintenance free, and design changes were recommended for different types of structures.

Also in the early 1980s, electrical utility engineers noticed that many of the tower joints were suffering from a condition known as "pack-out." Corrosion products of the weathering steel built up in crevices, causing severe distortion of the steel members. Subsequent research funded by the utility industry indicated that this condition did not present a significant structural safety risk for the vast majority of the structures. Nevertheless, some utilities have elected to protectively coat these joints, and further use of weathering steel for this application has been limited. Concern has also been expressed about the joint areas of weathering steel light poles.

In the late 1980s, the steel industry launched a new promotional strategy which recognized the limitations of weathering steel and sought to inform engineers and architects on how to best utilize the product. In the last year or so, several comprehensive consensus type reports and guidelines have been issued, codifying the results and experience of the previous 10 years.

Conditions for Forming Protective Oxide

The precise mechanisms of oxide formation and the structure of the oxides are not fully understood. However, the conditions for forming the protective oxide have been clearly identified. It is essential that the steel be subject to alternate wet and dry cycles. The oxide must be able to absorb and desorb water to form the tight crystalline structure needed for the patina. If the steel is continually or even mostly wet, the oxide will be loose and flaking like that for carbon steel.

Another requirement is that the surface be free of chlorides or other aggressive species such as sulfides. The chlorides interfere with the oxide formation, causing pitting and localized corrosion. Other contaminants such as sulfur compounds, acids, and chemical fumes should also be avoided.

In order to achieve the alternate wetting and drying, a condition known as "open bold" exposure has been stipulated. This allows the steel to be exposed to the elements (i.e., rain, wind, and sun) to produce the wetting and drying action.

Conditions to Avoid

In order to help ensure that the protective oxide is properly formed, industry has identified certain environmental and structural conditions that should be avoided. "Tunnel-like" configurations on highway overpasses can result in increased corrosion rates. This results from a depressed roadway with high sidewalls, creating a tunnel-like condition. This allows salt, dust, and dirt to accumulate, and shelters the steel from the atmosphere.

Marine conditions (e.g., from road de-icing salts or proximity of salt water) are detrimental

because of the effects of chloride. Thus, a major cause of corrosion on bridges is leaking bridge joints, which allow salt-laden water to run over vertical surfaces and collect on bolts, flanges, and other horizontal surfaces.

Weathering steel was also not designed for immersion service or burial in soil. Also, a poorly protective coating will do more damage and harm as it allows moisture to penetrate between the coating and the steel and to collect there.

Remedial Maintenance

The previous conditions are primarily suitable for designing and planning of new bridges and structures. What can be done about the thousands of bridges and other structures which were previously erected and which may include some of the conditions described?

Several guidelines are available for retrofitting weathering steel bridges. Remedial Maintenance Options are as follows:

- ◆ *No action (deferral)*

The first option is to defer any painting or other action at least until the next inspection period (should be no more than 2 years). This option is recommended when scaling of the oxide is moderate, corrosion is uniform, and there are no critical joints affected.

- ◆ *Protect damaged areas only*

A second option is to clean and paint only those areas most vulnerable to corrosion damage. These include leaky joints and bottom flanges. Several state DOTs require painting within 5 to 10 feet of the joint.

- ◆ *Protect entire structure*

A third option is to clean and paint the entire structure. This is recommended for bridges where salt is deposited or condensing humidity conditions prevail on large portions of the bridge. Where a contractor has erected scaffolding or brought in blast cleaning equipment, it may be more economical to clean and paint the entire structure rather than limit it to the areas considered most vulnerable.

- ◆ *Preventive maintenance (nonpainting)*

This option includes drainage improvements such as troughs and periodic inspection and maintenance of joints.

Because of the tighter oxide and rougher surface, removal of the oxide (e.g., by blast cleaning) is more difficult and costly than similar operation on carbon steel. Also, a larger amount of paint will be needed to fill in the profile. Another factor which increases the cost of cleaning and painting weathering steel is the lack of familiarity of most contractors in working with this material.

Therefore they do not have the experience in optimizing the type of abrasive, the angle, distance, and pressure, and other practical aspects.

The particular option chosen depends on factors such as the economics, the perceived risk to safety, DOT or other agency policy, and environmental factors.

Life Cycle and Economics

In order to analyze the life cycle cost of weathering steel, one requires a certain amount of data. These data may differ significantly among different bridges so there is no single analysis that can be done to determine the economic comparison of different bridge construction and protection methods. The following types of data are necessary to do a thorough analysis:

- ◆ *Steel fabrication and erection costs*
carbon v. HSLA steel
painted v. unpainted
- ◆ *Time until maintenance required*
- ◆ *Cost and effectiveness of maintenance*
- ◆ *Savings/cost to environment.*

Some analysis has been done comparing unpainted weathering steel, painted weathering steel and painted carbon steel. Oftentimes the data used are based on estimates or projections and reflect the bias of the person presenting the data.

Generally the cost for the initial fabrication, erection, and painting are readily available, although these also depend on the specific structure, configuration, and environment. The time until maintenance required is more difficult to determine, as it is based on judgment about condition of the steel and design life and safety factors. Aesthetics can also be a factor here.

To determine the cost and effectiveness of maintenance therefore requires developing specific criteria for the need for maintenance and the measure of effectiveness.

An important new element in the equation is the impact of these operations on the environment. Use of unpainted weathering steel eliminates VOC emissions. There may be a value that can be assigned to that environmental savings. There is a need, then, for an objective, comprehensive evaluation of the cost and life cycle of weathering steel to determine how well it competes with conventional painted carbon steel.

ADVANTAGES OF WEATHERING STEEL

The major advantages in using uncoated weathering steel are as follows:

◆ *No surface coating needed*

Elimination of need for a coating is the reason this technology has been presented at this conference. The material thus eliminates the planning, execution, inspection and maintenance which are necessitated by the inclusion of a protective coating on a steel substrate. Related advantages are given below:

◆ *Eliminate VOCs and other hazards*

Coatings are a major source of VOCs which contribute to ground-level ozone. This aspect would be eliminated, along with the health risks from solvents and other paint ingredients and the health and safety risks from blast cleaning and other removal operations.

◆ *Reduce construction and maintenance costs*

The application of a coating is estimated to add 10-20 percent of the construction and erection cost of a bridge. Painting is also a major component of the maintenance cost for bridges or other industrial structures.

◆ *Higher strength steel*

Weathering steel being a high-strength steel would require a reduced amount (and therefore weight) of steel for construction purposes. This would also reduce the cost and allow alternative designs to be utilized.

Disadvantages

Weathering steel also has a number of disadvantages which are summarized below:

◆ *Not suited for certain conditions*

Among conditions where weathering steel should not be used are high-chloride, continuous condensing conditions, areas where moisture can collect, "tunnel-like" conditions, and any configuration or environment where alternate wetting and drying will not be achieved.

◆ *Not maintenance-free*

Regular maintenance of weathering steel is required, even where the required oxide formation conditions are expected. Joints should be inspected and cleaned periodically, and steel members should be measured for corrosion loss and pitting. Other maintenance practices may also be needed.

◆ *More costly to protect if corroded*

Removing the tight oxide layer is more difficult and costly for weathering steel than for carbon steel. In addition, if chlorides become embedded in the steel, special methods (e.g., wet blasting) may be required.

- ◆ *May pose structural (safety) risk*

The buildup of scale on the protective oxide layer may hide problems such as fatigue cracks, or pitting, which could affect the structural integrity.

- ◆ *Questionable aesthetics*

One aesthetic factor is the color, which ranges from a dull light brown to a dark dull brown, and which has a rusted appearance. Another concern is the staining. The oxidation of weathering steel produces continual light flaking, which can produce a sometimes unsightly stain on the adjacent concrete or other surfaces.

Recommendations

Recommendations are categorized as shown below:

Recommendations for New Structures

- ◆ *OK for most non-salt environments*
- ◆ *Use new designs to avoid water collection*
- ◆ *Consider partial painting for corrosion-prone areas*
- ◆ *Plan for maintenance*

Recommendations for Existing Structures

- ◆ *Inspect every 2 years*
- ◆ *Clean and paint salt- or moisture-laden areas*
- ◆ *Retrofit to improve drainage*

General Recommendations

- ◆ *Follow design and maintenance guidelines*
- ◆ *Develop database and model on performance and cost*
- ◆ *Emphasize environmental benefits*
- ◆ *Identify new uses*
- ◆ *Objectively encourage use (do not over-sell)*

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PAINTING THERMOPLASTICS WITH A FILM

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Abstract

Today, thermoplastic parts can be "painted" with film. This is accomplished by laminating the "paint" film onto a variety of plastic substrates. Either injection or vacuum moldings exit the molding operation painted. There is no further processing required. The traditional painting operation can be eliminated from the production process.

This process has been proven to yield parts that exhibit very smooth surfaces, which are extremely durable. Exterior automotive coatings, as well as more "normal" coatings, have shown superior weather resistance. A multitude of automotive parts have been produced by this method. Some include: truck fairings, van claddings, automobile trim parts, tractor fenders and automobile doors.

The process has been commercialized and used on interior automotive parts for several years. The development of exterior coatings that maintain appearance and durability characteristics is what is broadening its use. Both Chrysler and General Motors have approved the system for use on 1993 model automobiles.

INTRODUCTION

One of the biggest drivers of change in the U.S. and Europe is the need to reduce solvent emissions from our paint shops. This need to reduce solvent emissions has forced the automotive industry to convert to high solid paint systems even though they do not produce an appearance that is as smooth and glamorous as low solid paint systems. Now, spurred by the Bush administration's tougher stance on clean air, the industry has accelerated toward even less polluting systems such as waterborne paints, which still contain up to 25% solvent.

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This movement to a clean environment is not without its costs. A paint shop typically makes up 30 to 50 percent of an assembly plant's costs. Building an automotive paint shop can cost from \$150 million to \$450 million or more, and the new environmental regulations will add to those costs.

Despite these rising costs, the paint job is one of the first things a shopper notices about a new car. Fit and finish became household words in the 1980s.

This focus on environment, quality and cost has led to increased technological activity in coatings. One of these recent developments is the paint film laminate process.

This process offers a production-ready method for painting thermoplastic parts without spray painting. This is accomplished by insert molding a paint film laminate that has been thermoformed into the shape of the finished part. The injection molded part is ready for assembly without subsequent finishing.

Since the 1970s, insert molding of thermoplastics has been used extensively for putting woodgrain patterns on instrument panels, consoles, gloveboxes and doors. The Decorative Films Division of Avery has been a leader in this field.

In the 1980s, weatherable exterior films have been laminated to thin gauge aluminum and used on pillar posts, window surrounds and rocker moldings as a replacement for spray painting.

The purpose of this paper is to describe how these two technologies can be joined to produce a painted thermoplastic part without spray painting. We will cover how the paint laminate is manufactured, how the paint laminate is used to produce a painted part, and the benefits of the process versus spray painting.

Painting by the insert molding process offers several unique advantages over spray painting, including:

- ◆ *elimination of volatile organic compound (VOCs) from the painting operation*
- ◆ *very smooth, high glamour finishes and bright metallics*
- ◆ *ability to use designs with multiple coats or printed pattern included in the paint*
- ◆ *removing the paint bake oven temperature requirements for thermoplastics.*

Paint film laminates and insert molding technology is at a point where it can be considered a viable method to paint exterior thermoplastic parts. Designers and engineers can now have the option of using this process for production applications.

DEFINITIONS

At this point in the paper it is best to define the terms that will appear later in the text to give readers a common understanding.

Paint Film - A cast-dried continuous coating of paint. It can be a monocoat, a clear coat over a base coat, or a clear coat that has been reverse printed (gravure) with a pattern before the base coat has been cast behind the clear.

Laminate - A composite of a paint film adhered to a thermoplastic backing sheet.

Backing Sheet - A thin (generally .020"), smooth, gel-free, thermoplastic sheet to which the paint layers are adhered.

Carrier Sheet - A flexible, foldable, heat-resistant, self-supporting sheet of polyester film on which the paint coating is cast and dried. The carrier sheet is only temporary and is removed prior to vacuum forming the laminate.

Size - A thin layer of resin that promotes the adhesion of the paint film to the backing sheet.

Preform - A laminate that has been vacuum thermoformed into the shape of the final part (or the painted area of the part) and the excess laminate has been trimmed away.

Insert Molding - An injection molding technique where a preformed and trimmed laminate is inserted in the cavity side of the injection mold, and this preform is fused to the face of the injection molding substrate during the molding cycle.

Injection Cladding - The process of insert molding a painted or decorated preform to obtain a finished part. Often used interchangeably with insert molding.

Weatherability - The property of being resistant to gloss loss, cracking, color change or otherwise degrading when exposed to severe climates for extended periods of time; meeting automotive exterior durability requirements.

MANUFACTURING OF THE PAINT FILM LAMINATE

Coatings

The paint laminate requires the use of unique high-performance paints that are capable of retaining their properties during thermoforming and injection molding. The paints used must not only provide the appearance, durability and weatherability required for the finished part, but must also exhibit elongation of 150% or more to thermoform properly.

The paints are coated via a reverse roll process onto a heat-resistant, smooth, high-gloss polyester film. The coating is dried in a long multi-stage oven. Coating is done in the reverse order as the first coat on the polyester becomes the first layer seen after the process is completed. The

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polyester film is discarded. It is the carrier or solvent of the paint film.

For clear coat/base coat systems, the clear coat is cast first (1 to 2 mils in thickness depending upon the application and the part geometry). Next, the color coat is coated behind the clear coat (generally to a thickness of .8 to 1 mil) and dried in a second pass through the multi-stage oven. Finally, a thin layer of size is coated on the back of the color coat to promote adhesion to the backing sheet.

Volatile Organic Compounds

VOCs are routed through an incinerator for destruction. This control of VOC emissions is required to meet environmental standards even though a very low solids paint is used to provide high glamour finishes.

Smooth Finish

Paint smoothness and high brightness are other significant advantages of the paint laminate process over spray painting. Using the reverse roll coater, it is possible to lay down extremely smooth paint coatings, providing a surface without orange peel or texture. This smoothness is especially evident with metallics. Because the paint is applied horizontally to the carrier film to a precise thickness, color consistency can be tightly controlled. This can provide an advantage over spray painting where part geometry and position on the vehicle affect the film build and color control.

In addition to bright metallics and the elimination of orange peel, the laminate painting process offers printed patterns or designs. In this case, the clear coat can be reverse printed by gravure to produce most any type of graphic, vignette or other pattern desired for the end application.

The laminate painting process provides the ability to apply three or four coats including intermediate pearlescent or double clear coats. This is generally considered to be uneconomical by spray painting.

The process can obtain different textures or gloss by varying the injection mold tooling. The paint film replicates the surface of the mold so if extremely high gloss is required, the mold should be highly polished.

Laminating to the Backing Sheet

After the coating process, the paint film is dry-laminated to a backing sheet by the use of heat and pressure. The backing sheet must be composed of a thermoplastic material that can be extruded into a readily thermoformable, gel-free sheet that will provide a smooth surface. Typically, an injection molding resin will not provide a backing sheet of acceptable quality.

The backing sheet must be compatible with the injection molding resin since, during molding, the two must form a permanent bond. A backing sheet of (ABS) would generally be used for injection molding with ABS and thermoplastic polyolefins (TPO) with TPO.

But it is possible, and sometimes preferable for part performance, to use a different modulus for the backing sheet than for the injection molding resin.

Other important considerations for the backing sheet are its sensitivity to moisture, its thermoforming process window, its brittleness and its ability to be pigmented when required.

The typical thickness of a backing sheet, excluding the paint layer, is .020". This is thick enough to handle the paint laminate in production yet not too thick to significantly reduce melt flow during injection molding. Also, a backing sheet of this thickness has the capability of hiding glass or other fillers used in many injection molding resins.

Protective Carrier Film

The paint film laminate is supplied in roll form in the desired width with the temporary carrier sheet left on to protect the paint surface during shipment. However, the carrier sheet must be removed prior to thermoforming.

Alternative Laminating Process

It is also possible to extrusion laminate the paint film to a thick thermoplastic sheet (.075 to .500"). This would be done by introducing the paint film at the extruder nip just prior to the embossing rolls. This "pre-painted" thick sheet would be used for thermoforming parts such as truck fairings, snowmobile covers and fenders that would otherwise be spray painted.

HOW THE PAINT LAMINATE IS USED TO PROVIDE A PAINTED PART

The paint laminate system is designed to be applied to the surface of the molded part in a two-step process. First, the laminate is thermoformed in the shape of the finished part and the formed laminate (preform) is inserted into the cavity of the injection mold for the part. As the part is molded, the backing sheet of the laminate bonds to the injection molding resin and creates a painted surface on the part.

Thermoforming

Thermoforming the paint laminate is similar to thermoforming other materials of like polymers and gauge. They can be formed on standard thermoforming equipment. However, a web-fed, in-line former with pressure assist would be preferred. Adequate control in the heating step is critical to provide proper part definition. The process conditions for thermoforming are primarily dictated by the backing sheet; the paint film has a very broad range of thermoformability.

The laminate is unwound from the roll and secured on its outer edges, indexed by transport chains through the heating oven zones, and thermoformed over a male mold with the unpainted surface in contact with the mold surface. The preform is then indexed onto a trimming station and trimmed.

Most molds will be constructed of aircraft gauge cast aluminum with cooling/heating channels to maintain the mold surface temperature at a specified level. Thermoforming detail and precise

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fit of the preform to the injection mold is critical to achieving a high-quality finished part.

Dimensioning of the thermoform mold is based on the area of the finished injection mold surface as well as the allowance for the preform thickness and the shrinkage of the preform. Also, part geometry and thermoforming conditions will affect the preform shrinkage.

Hardened steel matched metal shear trimming die set is recommended for trimming the preform on a mechanical or hydromechanical press. Proper planning of how the preform is to be trimmed is important to avoid unpainted edges showing in the finished part. Care must also be taken to avoid damage and to maintain cleanliness of the preform - which will become the painted surface of the part - during handling, storage and shipping.

To recap, critical variables for thermoforming include tooling, forming temperature and cycles, preform definition, fit of the preform in the injection mold cavity and edge trimming.

Injection Cladding

The trimmed preform is placed in the cavity side of the mold with the paint surface against the mold. A highly polished mold surface, without pores or defects, is required. The mold is clamped and the molten resin is injected into the mold cavity. The heat and pressure of the molten resin partially melts the backing sheet and forms a melt bond with the preform.

The mold must be rear- or edge-gated so that the polymer is directed onto the backside of the preform. Gating should be designed to provide a smooth, even flow front with a minimum of weld lines. The gate opening should be larger than normal to minimize the high viscosity flow and shear heat input on the preform.

When the mold is opened, a Class A finished part can be removed. This part should be handled with the same care as any other painted part.

Standard injection molding machines can be used. Access should be made for inserting the preforms and for removing the parts. A robot arm can be used to insert the preform and later remove the finished part. The molding cycle should only increase a few seconds for the insertion of the preform.

It is important that the preform be inserted properly. Misalignment could cause pinching, scuffing or polymer intrusion resulting in a visually defective part. Also, cleanliness of the mold surface and the preform is critical to achieving a quality finish. It is recommended that the mold area of the injection mold machine be isolated from the surrounding area.

Parts Considerations

Although painting an entire injection molded plastic car with the paint laminate process is possible today, it will be a few years before these automobiles are built. We will spend the next several years painting a multitude of parts on the automobile. Injection molded parts of many geometries have been molded using a painted preform. These include body side claddings, filler panels, doors, body panels and wheel covers.

Limitations of part geometry have not been fully explored, but parts with deep, side-by-side pockets, multiple undercuts or a series of thin slits would, at the very least, be difficult to thermoform and trim. Parts should be designed for this insert molding process rather than trying to adapt a part originally designed to be molded and spray painted.

ADVANTAGES OF THE PAINT LAMINATE PROCESS VERSUS SPRAY PAINTING

The advantages of the paint laminate process can be separated into those that are attributable to the process itself and those that are attributable to the paint system chosen by Avery for their Avloy® Painted Sheet product line.

Process Advantages

The advantages of the process can be separated into three areas: Environmental, Appearance and Manufacturing.

Elimination of VOCs generated during the painting process has a significant long-term benefit for a cleaner environment. The expense of continuously reducing emissions from existing paint facilities is eliminated. A safer work environment is provided. The painted thermoplastic parts can be recycled as injection molding resin behind the backing sheet.

Appearance advantages include low solids/high glamour looks and bright metallics. Graphics can be introduced along with color. Orange peel can be eliminated. The backing sheet can hide fillers and provide a smooth surface. The same paint can be used over multiple substrates and will still match.

Manufacturing advantages include the use of low-heat-distortion plastics or solvent-sensitive plastics and no capital for paint shops. The process is also compatible with modular assembly.

Avloy® Paint System Advantages

The thermoplastic paint system chosen for Avloy® products meets all of the paint requirements for a leading automotive (OEM). In addition, it is more weatherable than existing commercial automotive clear coat/base coat enamels. It has superior resistance to gasoline, solvents, chemicals and acids, including acid rain, when compared to existing commercial automotive finishes.

CONCLUSION

It is now possible to obtain a high-quality, extremely smooth paint finish on thermoplastic exterior body claddings and moldings without spray painting. This can be achieved by insert molding a paint film laminate that has been thermoformed into the shape of the finished part. The injection molded part is then ready for assembly without subsequent finishing.

Unlike in-mold coating and mold-in-color, this laminate painting process provides high-gloss metallics and nonmetallic finishes. Graphics in combination with paints are also available.

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Even though most of the examples on the paint film have been directed at the automotive industry, the technology and process can be adapted to any injection molded or vacuum formed part.

The laminate coating process has proven to be cost competitive with spray painting when the total cost of producing a part is considered.

The paint laminate finish provides superior weatherability and acid etch resistance. Perhaps best of all, the paint laminate process is virtually pollution-free and provides a safe worker environment.

TEDLAR PVF FILM COATING APPLICATIONS

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When I was asked to talk about the possibility of lowering VOC emissions through the use of Tedlar PVF film I realized that I had an easy task. Tedlar has been used commercially as a weatherable surface on many substrates for over 30 years. With that long a history, Tedlar provides a benchmark of what has happened in the reduction of VOC emissions over that time span. Tedlar has reduced VOC emissions in three phases of coating operations. First, emissions during the manufacture of the surfacing material, Tedlar; second, emissions while coating materials with Tedlar; and third, emissions that occur during refinishing operations over the life of the coated product.

Let's take a look at just what Tedlar is. It's a film made from polyvinyl fluoride, a product of Du Pont's fluorocarbon research in the 1940s. PVF is a polymer made from vinyl fluoride or monofluoroethylene monomer. Other products from that same research include PVF2 made from vinylidene fluoride or difluoroethylene and Teflon made from tetrafluoroethylene. As part of the scouting to determine the properties of these new polymers, films were prepared. The weather resistance of these films was evaluated in both accelerated and actual exposures. After 10 years outdoors the PVF sample had lost little of its physical properties. In the mid 1950s DuPont began a program to make a weatherable film product. Tedlar was the result of that program. Building products coated with Tedlar have been commercially available since 1961.

What makes PVF a weatherable polymer? Partly it's the fact that PVF is transparent to UV down to 280 nm. The lowest wavelength in sunshine that reaches the surface of the earth is about 320 nm. So PVF suffers no degradation by sunlight. The chemical resistance, though, is the phase of weatherability most germane to today's discussion. This, as you all remember from junior high school chemistry, is the Periodic Chart of the Elements. As you further recall, the closer to the top and the further to the right an element falls, the more electronegative it is. That means the element has a strong tendency to attract electrons. That's fluorine in yellow in the upper right. This slide depicts the fluorine atom with its nucleus as a light blue circle at the center and its two electron shells. The atom needs one electron to complete its outer shell. The yellow circle

represents the missing electron. All other elements either need more electrons to complete the outer shell or, because they have a greater atomic number, have more electron shells. This puts the missing electron farther from the protons in the nucleus. In either case, the attraction for the electron is lessened. Here's a schematic of the PVF molecule. You can see the carbon/fluorine bonds in yellow. They form the major portion of the polymer. On a weight basis the one carbon atom and the fluorine atom together comprise two-thirds of the mass. This next chart shows the energy needed to break various organic bonds. Far more energy is required to sever the carbon/fluorine bond than to sever the bonds found in other polymers. This energy to deteriorate a polymer can come from UV, chemical reactions, or solvents. The more energy needed to break the bonds, the more stable the polymer is. Looking at the PVF molecule again you can see that it has more than just carbon/fluorine bonds. While these other bonds, carbon/carbon for example, are not as strong as the carbon/fluorine bonds, they are protected by the steric hindrance of the fluorine atom. The explanation of steric hindrance is beyond junior high chemistry. It's even beyond chemistry for chemical engineers, so we'll end our science lesson now. Suffice it to say Tedlar is not damaged by UV, oxidation, hydrolysis or other chemical reactions.

These properties are impressive but they remind me of the dilemma of the old alchemist who was searching for the universal solvent that would dissolve all matter. A simple peasant on hearing what the alchemist was looking for asked him, "What are you going to keep it in once you find it?" The chemical resistance of PVF lead us to the dilemma that since it is such an intractable polymer, how do you make a film from it? A second question could be what does this have to do with reduced VOC emission? First let's look at the way Tedlar is made. At our plant in Buffalo, New York, we begin by polymerizing vinyl fluoride monomer. The resulting PVF polymer cannot be dissolved in a solvent and cast as a film. It cannot be melt extruded. We make Tedlar by mixing the polymer with dimethyl acetamide, DMAc. Under the heat and pressure of an extruder the DMAc causes the PVF to form a gel film. The gel film is stretched and the DMAc evaporated in the orientation step. All the DMAc is recovered by distillation and cycled back to the mix area. The process was designed in the 1960s as a closed system because of the cost of DMAc and, more importantly, a lack of knowledge of the harmful effects of DMAc. With 30 years' experience we have found that some of our fears were groundless but we still operate a closed system and recover all the volatile matter. We make and ship film with no emission of volatile organic substances.

How do our customers apply Tedlar as a surfacing material and how does this affect their VOC? This is a good time to look at how the whole field of applying coatings has changed over the last 30 years. In the early 1960s the major concern with solvent-based coatings was fire. As long as the solvent concentration in the coating room, in the processing ovens and in the exhaust stack stayed below 25 percent of the lower explosive limit, the operation was considered safe. Other than fire safety, little concern was expressed about what went up the stack. Solvents were cheap and most coating operations were small. Two things happened in the early 1970s to change this attitude. Solvent costs rose with the rapid increase in petrochemical prices, and air pollution control legislation such as Los Angeles' Rule 66 went into effect. At this time it became evident that venting solvents to the air was a bad practice both socially and economically. These actions gave impetus to the concept of prefinishing articles rather than postfinishing them. In prefinishing, stock is coated in its flat state and the finished material is shaped and assembled into the final part. This is in contrast to postfinishing where the assembled part is fabricated and then

coated, usually by spraying or brushing on the finish. Here a sheet of plywood is being laminated with Tedlar in a plant. This military housing at Loring Air Force Base in Maine is sided with prefinished wood. No field painting was needed. The housing was completed with no VOC emission. Here the reduction in solvent emissions during the original installation was further enhanced by the long life of the Tedlar surface. The Department of Defense expects to have to refinish painted siding every 5 years. These houses were 15 years old when the photo was taken and still looked new. Prefinishing reduces emissions in two ways. First, since the prefinishing tends to operate on a larger scale than post painting, the emissions are concentrated in one location and can be monitored and controlled. In some instances the control costs nothing. The solvent is removed from the exhaust air by a catalytic burner. The heat gained in burning the waste solvent is pumped into the coating ovens. The fuel saved pays for the cost of the equipment used to clean the exit air. Here's a brochure from a company called REECO. Their customers are recovering 85 percent of the energy from the solvent in the coating oven exhaust. That's not just removing 85 percent of the solvent; all the solvent is removed and 85 percent of the theoretically available energy is recycled to the oven.

In addition to plywood siding, steel, aluminum and hardboard siding came into use; even windows were supplied with a factory applied finish for replacement and new home construction. The products are coated in 20 or so plants around the country. These plants operate in compliance with specific standards both of measurement and control. Solvent emission is far less than that which would be produced by painting tens of thousands of homes by hand. Emissions are also reduced in prefinishing by coating a flat sheet rather than painting a complex shape. With prefinishing, a uniform coating is applied so less material is used to ensure a minimum coating. Less coating material means less solvent used.

Even compared to other coating materials used on a prefinishing line, Tedlar has the advantage of a longer service life. This reduces the VOC emission over the life of a structure by eliminating repainting. Here is a 15-year-old home in Columbus, Ohio. The siding is surfaced with Tedlar but the window sill was covered with aluminum prefinished with a baked enamel. The factory applied paint has eroded away; the Tedlar is as good as new. This house at the New Jersey shore used factory-painted aluminum for the downspout. In 20 years the paint is long gone. The Tedlar is fine. Based on 20-year-old installations, we estimate that Tedlar will last 50 to 60 years before erosion of the finish produces an objectionable appearance. The 80s brought a further reduction in VOC. Tedlar business in residential siding saw a drop in wood and aluminum substrates and a commensurate rise in solid PVC siding. A process for laminating to plastic materials has been used since the mid 60s. This process has been used to laminate Tedlar to scrim-reinforced PVC for awnings, air-supported structures and recently for blimps. The system worked perfectly for the new siding. Adhesive-coated Tedlar is combined with freshly extruded polymer in a nip roll. The heat of the extrudate melts the thermoplastic adhesive forming the bond. Since the Tedlar is supplied adhesive coated, no solvents are used in the surfacing operation. By using adhesive-coated Tedlar, our customers reduce the number of sites where solvents are used. Worldwide just three facilities are used for applying adhesive to Tedlar for plastic laminations. Twenty to thirty plants, surface plastic materials with adhesive-coated Tedlar and produce no VOC. In fact, solvent-free coating has become the norm in this industry. Surfacing equipment consists of a series of rolls. No solvent coating facilities exist. No ovens; no exhaust stacks. Because both the adhesive and substrate are thermoplastic, this application requires only one-third as much adhesive in comparison with lamination to aluminum. The adhesive melts and flows into the substrate. A 67

Tedlar PVF Film Coating Applications

percent reduction in adhesive means a 67 percent reduction in solvent used to apply the adhesive.

Another solvent-free coating operation provides panels for trailers used in the trucking industry. Tedlar is laminated in a press setup to cured polyester-coated wood panels large enough to provide the entire wall of this trailer. Here the reduction in solvent emissions is the result of the durability of the Tedlar surface. This truck will not need painting for at least 10 years. Depending on the weathering conditions, an average trailer will be repainted three to five times over that time span. A trailer uses 3 gallons of paint with a total of 6 lb. of VOC for each refinishing job. That's 30 lb. of volatile organic solvents saved for each truck. Decals based on Tedlar film also reduce VOC emissions. More and more trailers are being thought of as moving billboards. A decal applied to the side of the truck produces no VOC emission. Painted decorations do. The decal retains its "like-new" appearance longer than paint. When a replacement is desired, the decal has to be stripped by hand and replaced with a new design. No painting is ever needed. Even small decals can add up to a large reduction in VOC emissions when a large number of those decals are used.

What's my outlook for the future of reducing VOC emissions after 30 years of using Tedlar as a surface coating? I'd say optimistic. The technology is there and it works. The desire is there. And certainly the need is there. It seems to me that change has come about more rapidly when tied in to a distinct economic advantage as in the case of vinyl siding replacing aluminum siding or in the case of a more durable finish on truck trailers reducing the need for repainting. The reduction in VOC emission was just coincidental in those cases. It probably isn't even appreciated. Maybe a public awareness campaign showing what has been accomplished can produce even more significant reductions. I also feel there is a place for legislation. This is a slower method of effecting change but in some cases it is the only effective way to clean up emissions. Legislation is also valuable in setting goals. Lastly I'm optimistic because groups like this are getting together to bring about progress.

MATERIALS RELATED TO THE NATIONAL AERO-SPACE PLANE

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INTRODUCTION

The ultimate goal of the U. S. National Aero-Space Plane Program (NASP) is the construction and flight testing of an experimental, fully reusable hypersonic aerospace plane. Called the X-30 it will be used as a piloted demonstrator of hypersonic flight and will be designed to have the capability of achieving earth orbit. It will use hydrogen-fueled, air-breathing ramjet/scramjet engines and will be capable of horizontal takeoff and landing. Representing a practical demonstration of a new generation of space flight, it will join a notable line of experimental aircraft that have been built and flown in the past to explore expanded flight capabilities. First flight is planned before the end of the century.

To meet weight and performance requirements, the NASP X-30 engines and airframe will make extensive use of uninsulated, load-bearing, lightweight structures. Active cooling with the hydrogen fuel will be used in many cases to keep temperatures within the capabilities of the materials, but to minimize weight it will be vital to have materials that combine low density with the highest possible temperature performance. Because of their potential for satisfying these needs, the materials classes of primary interest include titanium alloys, titanium-based metal-matrix composites, carbon-carbon composites, ceramic-matrix composites, and copper-matrix composites.

These and other advanced materials are important for use in load-bearing structures that will see high temperatures in both the airframe as well as the engines of the vehicle. They would be used on the airframe as lightweight skin panels of honeycomb-core, truss-core, or integrally stiffened thin sheet configuration. Where necessary, they would be cooled with the gaseous hydrogen fuel by incorporating coolant passages into the structures. They would be used in the engines as the wall panels in the hot gas path of the ramjet/scramjet and also in the inlet and nozzle areas. The

engine application represents a particularly challenging problem because of the severe environment, involving high thermal, acoustic and mechanical loading. In this case, the structural components will almost certainly have to be actively cooled, meaning that the materials may be in contact with hot hydrogen from the fuel in addition to hot oxygen and the gaseous products of combustion.

This paper describes the major classes of materials that are being developed and scaled up for the NASP program. It reviews the technical approaches in each of the materials classes and indicates the progress being made toward meeting the challenging structural requirements of NASP.

TITANIUM ALLOYS

Titanium-based candidates for airframe structures include high-temperature conventional titanium alloys as well as titanium intermetallics. The intermetallics are of special interest because they have essentially the same density as titanium but open up the possibility of much higher use temperatures. The two intermetallic systems that have been of primary interest are based on the Ti_3Al and $TiAl$ compositions, which have potential maximum temperature capabilities of about 815 °C and 980 °C, respectively.

The principal drawback of the aluminides is their limited ductility and toughness properties at temperatures less than a few hundred degrees. Coupled with the requirement for higher fabrication temperatures than conventional titanium alloys, this makes mechanical working methods – such as sheet rolling – more difficult to accomplish. The processing of product forms that require a large amount of metal deformation, such as thin sheet for honeycomb-core or truss-core panels, must be done in a carefully controlled manner to avoid cracking of the material during the reduction of the starting material to finished form. In addition, the practical use of the aluminide components in load-bearing structures must take account of the probability that their ductility and toughness characteristics will be limited in comparison to other materials, such as conventional titanium alloys. This mandates the careful use of well-characterized materials, in conjunction with reliance on behavior understanding and the employment of analytical life prediction methods.

In the NASP program, composition modifications and advanced thermal-mechanical processing methods are being applied to the intermetallics to improve their properties. The goal is to achieve a balanced set of properties that combines useful levels of strength with the best possible toughness and ductility characteristics. These modifications—particularly composition changes—must be done in a way that retains the low density and high temperature characteristics that make the aluminides good candidates as structural materials.

Such alloying and processing modifications have improved the properties of the Ti_3Al -based alloys significantly, and good quality sheet products are being produced that have reasonable levels of ductility. Sheet-processing methods for the harder-to-work $TiAl$ -based materials have also been developed, but have yet to be scaled up to an economical production

level. In terms of mechanical properties, the Ti_3Al -based materials can be regarded as good candidates for selected structural uses on NASP. In the case of the higher temperature $TiAl$ -based aluminide materials, a balanced set of mechanical properties – a suitable mix of strength, toughness, ductility, fatigue, and high-temperature properties – is still to be achieved; consequently, it is probable that their use on the vehicle will be limited to lightly loaded structures where their low ductility is not as critical.

Because much of the airframe and engine structure will be actively cooled, hydrogen at various temperatures and pressures will be in contact with many of the structural materials. Depending on its temperature, pressure and concentration, the hydrogen can interact adversely with most titanium alloys, leading to embrittlement. The titanium aluminides are more resistant than conventional alloys, but hydrogen-resistant barrier coatings will be needed for all the materials to some extent. The development of effective barrier coatings is an integral part of the program, and significant progress has been made using oxide-based coatings; however the severity of the hydrogen effects may limit the uses of titanium-based materials to non-actively cooled regions of the structure. Coatings for protection of the titanium-based materials against high-temperature oxidation are also required. In this case, surface modifications of the titanium, together with the application of glass-forming materials, appear to be promising and are being evaluated.

TITANIUM COMPOSITES

Metal-matrix composites based on titanium alloys and titanium aluminides offer significant improvements in stiffness and strength over their unreinforced, monolithic counterparts. This makes them important for the thin-gauge skin structures required for the NASP airframe skins. The basic technical challenge in making these composites is to incorporate reinforcing fibers into the matrix without creating excessive interactions at the fiber/matrix interface. If allowed to occur, these reactions would prevent the attainment of the full property potential of the materials.

The conventional method for fabricating metal-matrix composites – involving the hot pressing of sandwiches of matrix material and fibers – is normally difficult to accomplish with titanium aluminides. They require higher forming temperatures than conventional titanium alloys, and this leads to unwanted interaction of the matrix with the embedded fibers at the temperatures and times needed for consolidation. In addition, the thermal expansion mismatch between the fiber and the matrix can lead to cracking of the low-ductility matrix on cooling from the consolidation temperature. Similar cracking may also be seen during subsequent thermal cycling of the kind that would be seen in service.

An alternative consolidation approach that is aimed at circumventing these problems uses a rapid-solidification plasma-deposition (RSPD) process. In this method, the matrix material starts as a powder that is fed through a plasma arc to convert it into molten droplets. These are deposited onto reinforcing fibers that are spiral-wrapped on a large diameter drum, where the droplets are rapidly quenched to a solid state. Rotation and translation of the drum allows the buildup of a layer of matrix material on and between the fibers. This solidified deposit of matrix material, containing a single layer of fibers, can subsequently be slit and stripped off the drum, and several of these layers can be stacked together and hot pressed to make a multilayer composite.

The RSPD process has been demonstrated successfully with SiC reinforcements in Ti_3Al matrix materials, and useful mechanical properties can be obtained. The equipment itself has been scaled up to a pilot plant size that will allow the production of reinforced sheet material that is about 1 x 3 m in size. In addition, using modified alloy compositions, Ti_3Al composites are being made using the more conventional foil/fiber/foil methods. For the higher temperature $TiAl$ -based matrix materials, it is still not possible to make SiC fiber reinforced composites with reliability characteristics that are sufficient to prevent them from cracking on exposure to thermal cycling. Alternative fibers are under development that have a closer expansion match and a better chemical compatibility than is the case with the SiC fiber. While these appear to be promising, this class of composites will require further development to make them reliable structural materials, and it appears that the Ti_3Al -based materials will have a clear advantage for practical, load-bearing structural applications.

In recent development, it has been shown that advanced conventional beta titanium alloys – as distinct from the intermetallic aluminides – can provide useful properties when reinforced with fibers such as silicon carbide. It appears that such materials have the potential for use at temperatures up to about 800 °C, and they could well find extensive airframe use as load-bearing skin structure. They have the additional advantage that conventional foil/fiber/foil consolidation methods and tooling can be used to make them. Using such processes, the NASP program has successfully demonstrated the fabrication of various structural shapes that have been built up into large airframe components. These components make use of multi-ply panels and complex-shaped stiffeners, and they include cross-ply fiber layers and tapered cross sections. They are currently being tested in simulated NASP thermal and mechanical loading cycles. Data from small specimens of these materials indicate that they can withstand the thermal cycling that would be required for use on the NASP skin.

CARBON-CARBON COMPOSITES

Carbon-carbon composites have the potential for use as lightweight structures exposed to temperatures in excess of 1400 °C without the need for active cooling. Because of their inherent high-temperature capability, they are regarded as candidates for use on the NASP airframe as large, integrally stiffened skin panels on the hotter parts of the vehicle. In this case, they may be used either as structural, load-bearing components or as lightly loaded thermal protection panels located over a metallic substructure. They may be useful also for engine applications, though it is not yet clear whether they could withstand the high heat fluxes and severe operating conditions in the hot gas path of the engine.

In terms of availability as structural shapes, carbon-carbon composites are mature materials. There is a large base of knowledge available regarding their fabrication and practical use, and they have been used in a variety of applications. Several companies specialize in the manufacturing of carbon-carbon components, and there are several basic methods available for making them. Many of these methods start with an organic-matrix composite precursor, using additional processing steps that subsequently convert the matrix to carbon. The precursor composites are made using a variety of methods that range from multi-ply lay-ups to three-dimensional woven structural shapes. The actual carbon-carbon manufacturing stages themselves are time-consuming, and must be controlled carefully to give uniform properties and to avoid batch-to-batch variations, but the essential manufacturing processes are well-established.

Before they can be used as load-bearing, thin-gauge structural components for NASP, there are several special technical problems to solve. Chief among these is the need for effective oxidation protection in the hypersonic flight environment. Existing protection schemes, developed for other applications, usually involve multilayer coatings and sealants. These work reasonably well in situations where the material is taken up to a single high temperature and then cooled, but they face significant problems when exposed to the complex time and temperature cycles of the kind that would be experienced on the NASP vehicle.

The basic difficulty with the existing protection schemes is that they use outer protection layers of refractory materials such as silicon carbide. These work well chemically, but they can crack due to the induced stresses caused by the thermal expansion coefficient mismatch between the silicon carbide and the carbon-carbon substrate. To alleviate this problem, use has been made of additional interlayers that oxidize to form a glass that can flow and seal cracks. Unfortunately, these glasses do not flow readily at intermediate temperatures, which reduces their effectiveness over part of the temperature range of interest.

Recent advances in oxidation protection technology have improved the situation, and small coated coupons have withstood the cyclic-temperature loading typical of an NASP environment. The improvements include the careful tailoring of compositions and thicknesses of the various layers of protective coating and the use of additives to the matrix that inhibit the effect of oxygen that may pass through the coatings. These improved protection schemes are being scaled up and applied to the large, complex-shaped components needed for NASP, and flight-weight oxygen-protected panels about 1.3 x 3 m have been made.

In addition to structural shape fabrication, methods for joining or fastening carbon-carbon composites to themselves or to other materials are being developed. These include the evaluation of fasteners fabricated from carbon-carbon composites or ceramic-matrix composites, which would be used in place of refractory metal fasteners.

CERAMIC-MATRIX COMPOSITES

Like carbon-carbon composites, ceramic-matrix composites have the potential for use at temperatures in excess of 1300 °C, with the added advantage of a much higher degree of inherent oxidation resistance. Unlike the carbon-carbon materials, however they are not as mature as a class of structural materials, they have not been as widely used, and they do not possess the same broad base of manufacturing experience.

There are two general classes of ceramic-matrix materials that may be important for NASP: glass-ceramic-matrix composites, useful up to temperatures of about 800-900 °C, and advanced ceramic-matrix composites, potentially applicable at much higher temperatures. Glass-ceramic-matrix composites are relatively well characterized and can be fabricated into product forms such as honeycomb-core panels and truss-core panels, but they have a limited temperature capability. From an NASP point of view, there is a much greater interest in the advanced ceramic-matrix materials, such as silicon carbide fiber reinforced silicon carbide (SiC/SiC) and carbon fiber reinforced silicon carbide (C/SiC).

Significant improvements have been made in advanced ceramic-matrix composites technology over the last few years, and it is now possible for specialist companies to make quite large, complex-shaped parts that have the potential of withstanding the temperature cycles required by NASP. These are being evaluated for their structural capabilities, and they could find important uses in areas exposed to very high temperatures – such as the region behind the nosecap or leading edges. A particular interest in the ceramic-matrix materials for NASP stems from their inherent resistance to hot hydrogen, and they may be useful for actively cooled engine components.

The extent to which the ceramic-matrix composites can be used reliably in structurally loaded components has yet to be determined, but there is evidence that materials such as C/SiC have great potential. Like carbon-carbon, they could be used either as thermal protection panels or as structurally loaded components. It has been demonstrated that they can be fabricated into the needed structural forms, and it is now a case of fully characterizing their properties and determining the limits of their applications.

COPPER-MATRIX COMPOSITES

Because the NASP vehicle will make extensive use of actively cooled skin structure, there is a particular interest in materials that have a high coefficient of thermal conductivity. Heat exchangers or actively cooled skin panels must be designed to transfer large quantities of heat quickly and efficiently from one location to another. In addition, the high-temperature differences that could exist across sections of heated skin structure could lead to unacceptably high thermal stresses. For these applications, the structural materials themselves must have adequate thermal conductivity or else they must be protected with an actively cooled, high thermal conductivity barrier layer.

Copper-matrix composites are potentially useful for these applications. Copper in itself has good thermal conductivity, but it is heavy, and its upper use temperature is limited by its low mechanical properties. Pitch-based, high modulus graphite fibers that were developed for their high stiffness and strength properties also have excellent thermal conductivity along the length of the fiber – significantly better than that of copper itself. The addition of these fibers to copper to make a fiber-reinforced composite can reduce density, increase stiffness, raise the use temperature, and significantly improve the thermal conductivity of the composite compared to the unreinforced copper.

One approach to the fabrication of these composites starts with a process that places a layer of copper around each fiber in a graphite fiber tow. The coated fibers are subsequently packed together and hot pressed into a fully dense material containing a high volume percent of fibers. Individual plies of the composite are then stacked together and consolidated, using cross-plying to compensate for the directional effects of the fiber. Using available metal matrix processing methods, it is possible to fabricate complex-shaped parts that contain coolant passages within the structure. Experimental actively cooled components have been built for the NASP program and tested successfully.

Additional work in the general area of high thermal conductivity materials addresses discontinu-

ously reinforced copper composites. These are made by melting and casting alloys of copper and elements such as niobium. Because the niobium is essentially insoluble in the copper in the solid state, it is possible to use appropriate mechanical processing methods to form a material where the copper matrix contains a very fine strengthening distribution of niobium particles. The resultant composite retains the high thermal conductivity of the copper matrix but is strengthened by the dispersoid distribution.

More recently, powder metallurgy methods have been used to make higher strength discontinuously reinforced copper-matrix composites. The rapid solidification powder process allows the use of other alloying elements and leads to a finer distribution of the strengthening phase. While the thermal conductivity of the discontinuously reinforced composites is not as high as in the graphite/copper materials, the properties are more isotropic than those of the graphite/copper. Conventional processing methods can be used to fabricate various product forms from these materials, and rolled sheet material has been machined, formed and joined to make heat exchanger panels that contain an intricate network of cooling passages.

Both classes of copper-matrix composites probably will be used on the NASP vehicle, in both the airframe and the engines. In many cases, the copper composites may be used as a thermal protection barrier that is bonded or joined to an underlying structure of another material, such as titanium composites.

COATINGS

Coatings will play an important role for all materials used in the NASP airframe and engines, and they are a key part of the development activities for each material system. They can perform several critical functions, including control of temperature and protection against the environment. For temperature control, they are designed to have high emissivity and to be noncatalytic to the recombination of the dissociated gases present in the hypersonic airflow across the skin. This can lead to a reduction of several hundred degrees in surface temperature. For oxidation resistance, they can provide a suitable barrier that prevents contact of hot oxygen with the underlying material.

The coating issue unique to NASP arises from the need to protect the materials against the effects of the hydrogen used for cooling. Hydrogen diffuses readily through many materials, and, in some cases, it can react with the material to form brittle compounds. The development of hydrogen barrier coatings is a critical challenge, especially for coatings that are thin, lightweight, resistant to damage, and can be applied to complex shapes, including internal passages. Successful coatings most likely will incorporate multilayer protection schemes involving several thin layers of materials, each performing a contributing function. However, even with suitable coatings, it is probable that hydrogen-sensitive materials, such as the titanium alloys and composites, will not be used in contact with hydrogen—at least, not where the hydrogen is in hot gas form. Instead, the hydrogen will be routed through resistant materials, such as the copper-based composites, or through cooling tubes of suitable materials.

SUMMARY

The structural materials requirements for NASP are challenging. This is true for any air-breathing hypersonic vehicle, but this is particularly the case for a vehicle intended to have a single-stage-to-orbit capability. A vital requirement for such a vehicle to achieve its goal is the attainment of a low structural weight fraction. This drives the interest in high-temperature, lightweight materials that can be used in the vehicle structure.

The paper describes the general development activities under way in several key materials areas. Over the past few years, significant improvements have been made in these lightweight, high-temperature materials, and in many cases they are at a stage where large structural components are being built and tested. The paper does not cover several other materials classes that will be important also; these include organic-matrix composites for cryogenic tanks, aluminum alloys for internal structure and nickel-base superalloys for hot engine structure. In general, these other materials are well established and readily available for fabrication of demonstration structural components of the right size and shape.

While rapid progress has been made in the development of the advanced materials of interest, their intended use must be approached with caution. In addition to their high-temperature and lightweight capabilities, the materials must have the reliability needed for use on piloted vehicles. Thus, properties such as fatigue behavior, creep resistance, toughness, and ductility are especially important. Many of the newer materials will have some of these properties—such as ductility—that are at levels less than traditionally acceptable for long-lifetime conventional aircraft. In recognition of this fact, an important part of the NASP program is addressing behavior analysis, life prediction methods, and nondestructive evaluation techniques, in the belief that they will be the key to successful application of these newer materials on NASP.

The rate of progress over the last few years gives confidence that the materials and structures requirements for NASP can be met by the current advances being made in their development. While the exact configuration of the X-30 vehicle is still being defined, it is probable that many of these materials will find extensive use on this experimental aerospace plane that is intended to pave the way for the next generation of space flight.

Appendix C
Conversion Factors

Table C-1. Conversion Factors

To convert from:	Into:	Multiply by:
<u>length</u> centimeters (cm) meters (m) mil nanometers (nm)	inches (in) feet (ft) inch mil	0.393 3.280 0.001 3.937×10^{-5}
<u>area</u> ft ²	m ²	0.092
<u>weight</u> pounds (lb) tons (t)	kilograms (kg) kg	0.453 907.184
<u>temperature</u> °F	°C	0.555 (°F-32)
<u>volume</u> gallons (g) boardfoot (bf)	liters (l) ft ³	3.785 0.083
<u>pressure</u> pound per square inch (psi) lb/ft ² kip/in ² (ksi)	kg/m ² kg/m ² lb. force/in ²	2.926×10^{-4} 4.882 1000
<u>density</u> kg/m ³ lb/in ³	lb/ft ³ gm/cm ³	0.062 27.679
<u>flow rate</u> g/minute	l/min.	3.78
<u>misc.</u> watt/ meter K in/in/°F Btu/hr-ft ²	cal/ (sec)(cm)(°C) cm/cm/°C watt/m ²	0.002 0.555 3.154