Skirts and Seals for Surface Effect Vehicles

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The current status of the development of skirts and seals is reviewed. Modes of failure, loading conditions, and effects of environment, materials selection, methods of manufacture, system fabrication, and test methods are discussed. A series of recommendations is made that, if followed, should lead to the development of more durable skirts and seals.

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Report of the
Committee on Skirts and
Seals for Surface Effect Vehicles

NATIONAL MATERIALS ADVISORY BOARD
Commission on Sociotechnical Systems
National Research Council

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NOTICE

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard to appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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W. Denney Freeston, Chairman
Committee on Skirts and Seals for
Surface Effect Vehicles

ABSTRACT

Surface Effect Vehicles (SEV's) with weights up to 200 tons capable of speeds to 80 knots over water and land are in service. Considerably larger vehicles are under development.

The high speed and versatility of SEV's offer significant potential for military and commercial applications. However, the life of the fabric-reinforced, elastomer-coated skirt/seal systems on current vehicles is short; it is anticipated that even shorter skirt lives will be encountered on the larger, higher speed vehicles under development, limiting the military potential and commercial practicality of the SEV mode of transportation.

The skirts are subjected to a salt water, sand, marsh, or ice environment coupled with the dynamic loading induced by high speed operation. Their failure is a very complex, interdisciplinary problem that is not completely understood. Three major modes of failure are evident: 1) delamination; 2) abrasion; 3) tearing. These may occur separately or in combination, depending on: 1) vehicle size and design; 2) vehicle mission; 3) skirt and seal design; 4) skirt and seal material.

The current status of the development of skirts and seals is reviewed. Modes of failure, loading conditions, and effects of environment, materials selection, methods of manufacture, system fabrication, and test methods are discussed. A series of recommendations is made that, if followed, should lead to the development of more durable skirts and seals.

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CHAPTER 1

INTRODUCTION

1.1 Surface Effect Vehicles

High speed craft capable of travel over water and contiguous land areas are of significance for military, rescue, and commercial purposes. In the past these requirements have been met by use of conventional surface ships, landing craft, submarines, and aircraft. In the mid 1950's surface-ship and craft technology began to develop. These vehicles are craft "wholly or partially supported above the surface over which they are travelling by a continuously self-generated pressurized cushion of air which is retained beneath the vehicle and carried along during operation" (Trillo, 1971). By having the vehicle move above the water or land surface, the limiting effect of drag on the hull structure is reduced. Consequently, such vehicles can travel over water at speeds up to 100 knots, in contrast to conventional ship speeds of approximately 30 knots. Thus, such vehicles could become very useful in military or rescue service.

Speed alone, while of possible value in a few specific instances (e.g., eluding an enemy ship or weapon), is of little use in military and commercial applications. However, the possibility of achieving high speeds with effective payloads at reasonable cost and without degradation of crew, weapon, or cargo-carrying performance has generated an interest in surface effect vehicle technology within the Department of Defense (DoD). While the benefits of such systems for DoD applications are apparent, the following more fully highlight the potential impact of this technology. If a frigate size, 60-100 knot oceangoing surface effect ship, capable of handling helicopters and/or vertical take-off and landing (VTOL) aircraft were available, the range for detecting and engaging an enemy would be greatly expanded and the total number of ships required would be reduced. This reduction in the number of ships would in turn reduce the Navy's overall construction, operation and maintenance costs.

Additionally, the availability of an air-cushion landing craft capable of speeds to 50 knots could significantly change the nature of amphibious operations. A task force could be located at a considerable distance from shore and the landing craft could travel at high speeds to an inland target area.

At the present time, the U.S. Navy is examining the feasibility of both of these applications in the 3000 ton surface effect ship and amphibious assault landing craft. In addition, the U.S. Army, in the LACV program, is examining the military feasibility of using air cushion craft as amphibious lighters.

1.1.1 Basic Operating Principle

All surface effect vehicles operate in essentially the same manner. Air is drawn into the craft by high-speed fans and distributed to the area under the vehicle's structure, by means of metallic or elastomeric ducting. The pressure is sufficient to raise the vehicle to a selected height above the land or water surface. This lifting air, commonly called cushion air, is retained beneath the vehicle by either a peripheral flexible skirt or a combination of solid side walls and flexible bow and stern seal systems. Cushion air must be continuously resupplied because of the escape of air between the lower edges of the skirt and the surface, and losses due to movement of the skirt or seal system as it passes over obstacles such as waves.

When the vehicle is fully lifted, it is propelled forward, sideward, or backward by means of either air propellers, propellers submerged below the water, or water jets. Since the vehicle is travelling on a cushion of air, high speeds are attained rapidly at relatively efficient power levels.

This need for continual regeneration of the air cushion limits the vehicle in terms of gross weight and the height that it can be lifted. This in turn determines the vehicle operating limitations (sea state or obstacle clearance height over land). Existing vehicle sizes range from 7 to 200 tons with cushion pressures of 15 to 100 per square foot and speeds of 30 to 80 knots.

1.1.2 Types of Surface Effect Vehicles

Although there is a variety of surface effect vehicles in existence, they can be classified into two general types; surface effect ships (SES) and air cushion vehicles (ACV).

1.1.2.1 Surface Effect Ships

Surface effect ships are those vehicles which employ hard sidewalls or hulls and flexible bow and stern seals to contain the air cushion (see Figure 1-1). During operation the sidehulls of these ships remain partially immersed in the water and the seals are generally in contact with the surface. Since these ships are not amphibious, submerged propellers or water jets are employed for propulsion. Speeds to 80 knots with 100 ton craft and cushion pressures of 100 psf have been achieved.

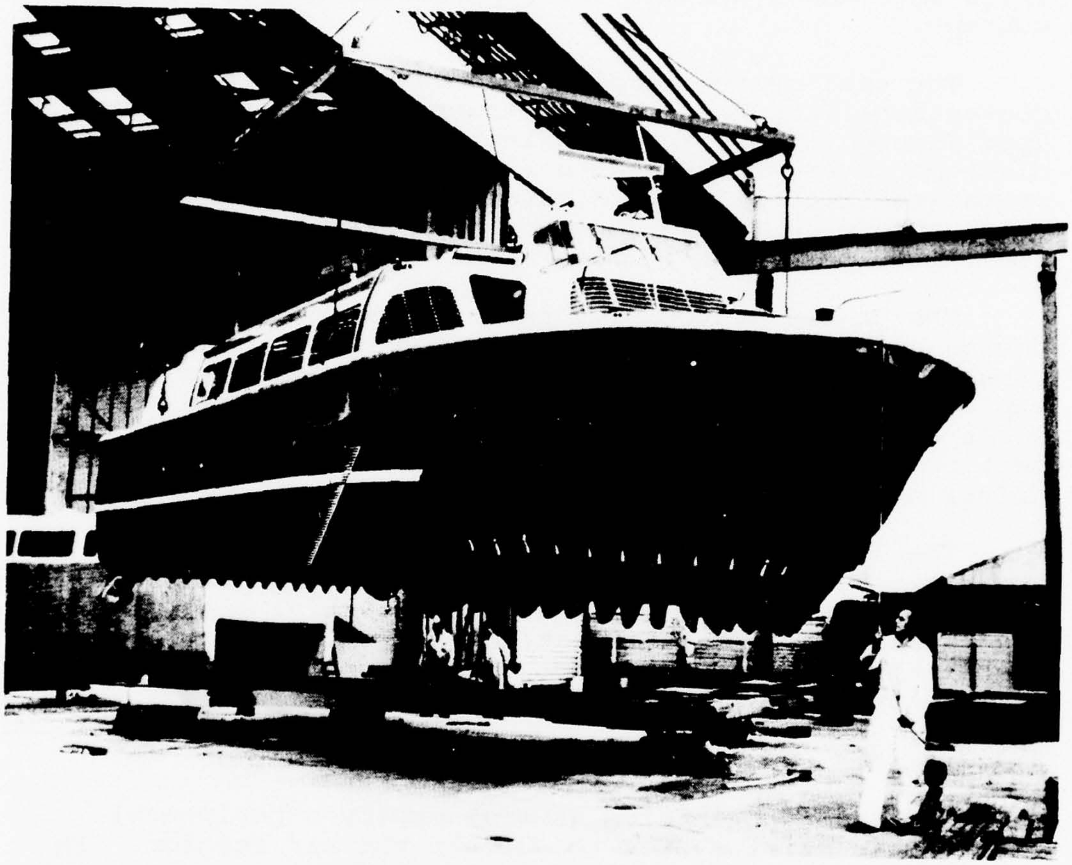


FIGURE 1-1 Surface effect ship (SES) (Hovermarine HM-2) (Mantle, 1975).

Early American efforts in surface effect vehicle technology utilized the sidewall and seal concept. Two 100-ton SES type vehicles have been constructed and are currently undergoing Navy evaluation. In Britain, The Denny 2 (23-ton) and H.M.2 (16-ton), passenger ships, utilize this concept.

The seal systems employed to date on these ships are conventional elastomeric bag/finger systems for the bow seal (see Figure 1-2(a)) and a series of overlapping, tapered, elastomeric bags arranged to form a planing type seal in the stern (see Figure 1-3). Elastomeric flat planing seals reinforced with fiberglass rods have been successful on a small navy test craft. (See Figure 1-4).

The United States Navy recently awarded a contract for design and construction of a 3000-ton SES which will be capable of operating as a fleet warship. This vehicle will employ articulated two-dimensional planer bow and stern seals fabricated from glass-fiber reinforced plastic sections attached to each other by flexible elastomeric joiner seals (see Figure 1-4).

The limitations of the surface effect ship in contrast to an air cushion vehicle are its non-amphibious nature and increased drag resistance due to the partial immersion of the sidehulls. These limitations are offset by greater stability, lower rate of loss of cushion air, and greater efficiency.

1.1.2.2 Air Cushion Vehicles

Air cushion vehicles (ACV's) employ a peripheral elastomeric skirt system to contain the air cushion. In normal operation over a flat surface, an air gap of one to six inches exists between the lower edges of the skirt system and the surface. The use of a flexible skirt permits travel over both land and water. Overland operations can be over ice, snow, marshes, beaches and low-growth vegetation. The height of obstacles which can be surmounted is a function of the skirt height. Depressions, such as ditches, with widths less than one-quarter the length of the craft, can be crossed with ease. For over water operation, the height of the skirt system establishes the height of closely spaced waves which can be traversed. Since these craft are amphibious, the primary propulsion method consists of large air propellers mounted on the upper structure. A few vehicles employ submerged propellers mounted on skegs below the craft structure and are therefore limited to over water operation. ACV's to date have achieved speeds to 70 knots with 200-ton craft using cushion pressures of 85 psf.

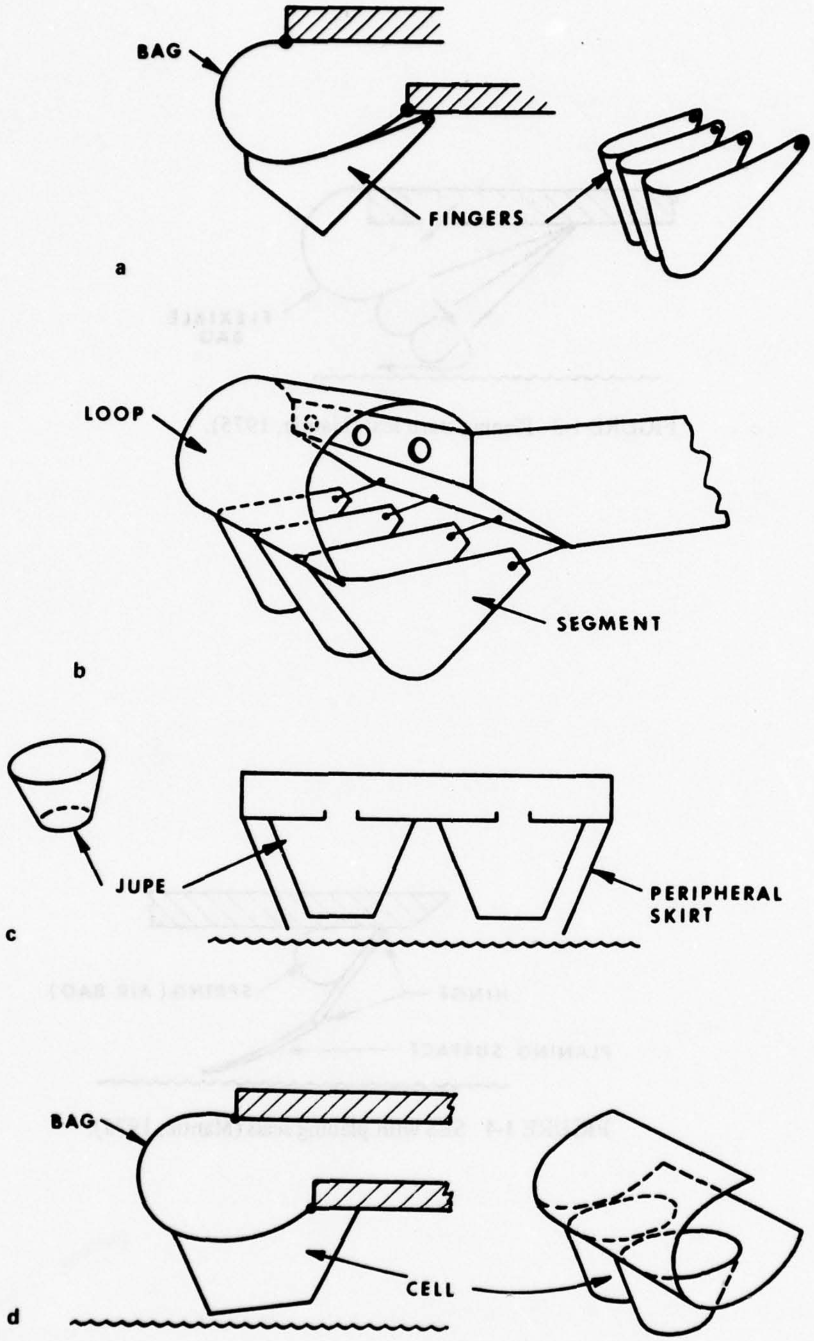


FIGURE 1-2 Basic skirt systems (Mantle, 1975).

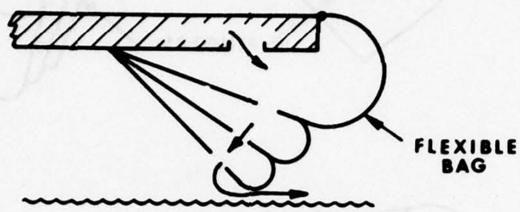


FIGURE 1-3 Planing stern seal (Mantle, 1975).

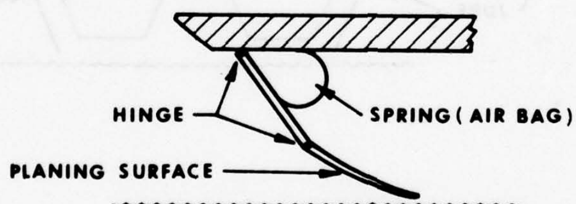


FIGURE 1-4 SES with planing seals (Mantle, 1975).

1.2 Skirt/Seal Systems

1.2.1 Design

The skirt systems employed for these craft to date are all fabric reinforced elastomers. Finger dimensions, and material strengths and weights used with various vehicles are given in Figure 1-5. The major components of the systems are:

a. the bag or loop, which is the primary means of ducting air from the lift fans to the cushion area

b. the fingers (segments, cells, pericells) which contain the air cushion and are in contact with or close to the surface

c. attachments used for joining bags to fingers, bags and fingers to hard structure, and for joining or reinforcing seams between segments of the bag

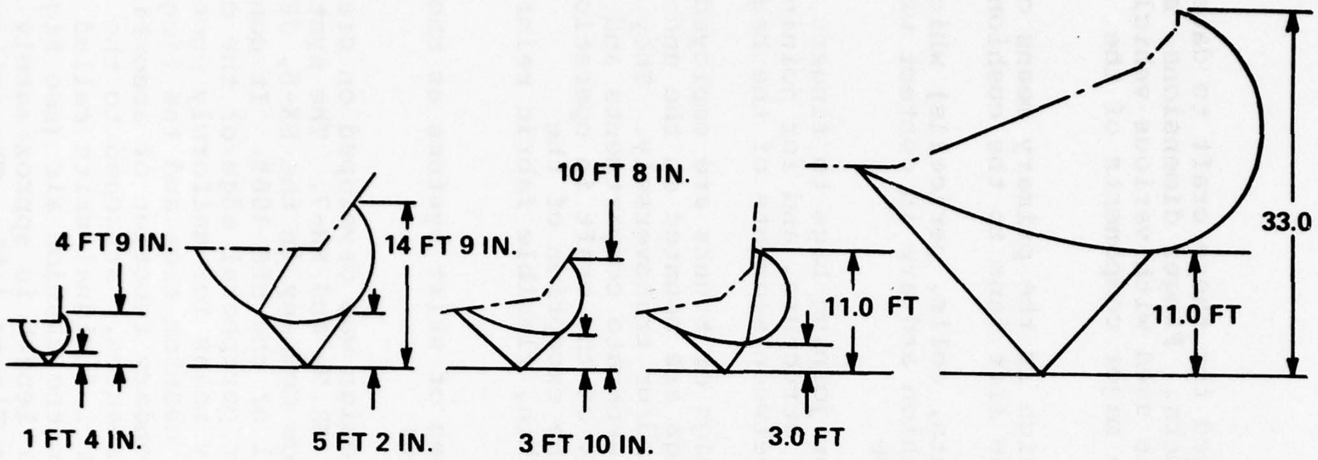
In addition, stability bags or trunks are employed with some skirt systems. These bags are mounted on the underside of the craft longitudinally and/or transversely. They divide the cushion area into separate compartments and thereby increase the stability of the craft in operation. All of the components, with the exception of the attachments, are relatively thin, flexible fabric reinforced elastomeric materials.

There are four basic types of skirt systems as shown in Figure 1-2 and described below:

1. Bag/Finger - This design was developed on craft such as the SR.N4, SR.N5, and SR.N6 and BH-7. The system is also employed by Bell Aerospace Company in the SK-5, JEFF-B Landing Craft and the bow seal of the SES 100B. It consists of a bag attached to the upper peripheral edge of the craft structure which is the primary means for uniformly ducting air from the lift fans to the cushion area and the fingers. The bag also performs the secondary function of absorbing impacts from high waves or obstacles. Attached to the lower part of the bag is a series of individual units called fingers which serve to contain the cushion air (see Figure 1-2a). In general, the finger length is approximately 30% of the total skirt height (see Figure 1-5). The articulated nature of these fingers allows the craft to traverse obstacles with a minimum loss of cushion air. For craft employing this system, individual segments called cones are used in the stern to retain the cushion air.

In order to achieve a greater degree of craft stability during operation, longitudinal and transverse trunks are

FIGURE 1-5 Current bag and finger skirt and seal practice (Bell Aerospace Corporation, 1977).



	SR. N6	SR. N4	SES-100B	JEFF(B)	3KSES	3KACV
TOTAL HEIGHT (ft.)	4.75	11.75	10.6	11.0	33.0	33.0
TOTAL WEIGHT (lb.)	1,000	10,200	4,300	10,000	74,000	210,000
CUSHION PRESSURE (psf.)	36	75	100	100	278	278
SPEED (knots)	30-50	40-55	60-80	45-70	60-80	80
CRAFT SIZE (tons)	15	75	100	150	3,000	3,000
FINGER MATERIAL STRENGTH (lb./in.)	850	1,200	1,000	1,000	4,000	4,000
FINGER MATERIAL WEIGHT (oz./sq. yd.)	83	140	-	90	-	-

mounted on the underside of the craft hard structure. These divide the cushion area into individual sections.

2. Loop/Segments - This design was developed by Hovercraft Development Ltd. (HDL) about 1965 and used on HD.2, VT-1, and VT-2 craft. It consists of an open loop attached on one side to the craft hard structure with finger-like segments attached to the outer edge and linked across to the underside of the hard structure (see Figure 1-2b). One advantage of this skirt system is the ease of access to the inner attachments of the segments, thus facilitating repair and maintenance. The full-depth segments also offer minimal resistance to obstacles, allow the use of lighter weight skirt materials and eliminate the need for dividing the cushion area with longitudinal and transverse trunks.

3. Bertin or Jupe Skirt - This design was developed by the French Bertin/SEDAM organization in the early 1960's. It consists of a number of separate cells or "jupes" mounted on the underside of the craft. Air from the lift fans is supplied to either individual cells or groups of cells. An outer skirt, in the form of a simple curtain attached to the hard structure, is employed to reduce leakage of cushion air and thereby increase the cushion area (see Figure 1-2c). This system has been used on the 5-ton BC8 and the 27-ton SEDAM N300 and will be used on the 200-ton N500, which is expected to be in operation during 1977.

4. Loop/Pericell - This design was developed by Aerojet General Corporation for use on the JEFF-A Landing Craft and SES-100A. The system consists of a loop which is attached to the upper peripheral edge of the craft hard structure and serves as the common air duct. Attached to the loop and craft hard structure are a series of individual pericells, which are essentially cone-like structures (see Figure 1-2d). Each pericell is fed air from the upper loop and thereby provides a means for achieving pitch and roll stability without the use of longitudinal and transverse stability trunks. In addition, the individual pericells are accessible for removal without the need for jacking up the craft.

1.2.2 Limitations of Skirt/Seal Systems

The major shortcoming of current surface effect vehicles is the relatively short life of the skirt/seal systems. These fabric reinforced elastomeric materials are subjected to the SEV operating environment of salt water, sand, marsh, ice, etc. coupled with the dynamic loading induced by high speed operation. Ten years ago a bag which provided 1000 hours of life was the goal. Today bags with lives in excess of 2000 hours are common. However, it is known that at some time after 2000 hours, the bags simply begin to deteriorate. Ten years ago, a life of 200 to 250 hours was still to be achieved for fingers. Three years ago SR.N4 bow fingers had an average life of 450 hours and today almost 500 hours. For fingers closer to the stern, and stern cones, life is still of the order of 160 to 200 hours. Stability bags have lives of about 300 to 400 hours.

For DoD applications, where higher speeds and greater cushion pressures are planned, shorter lives for skirt components are expected. This will impose a severe limitation on the military usefulness of SEV technology, although small-scale tests indicate that articulated, rigid, planer-type seals for SES may provide substantial improvement in life and greatly facilitate repair and maintenance.

1.2.3 Implications of Short Life of Skirt/Seal Systems

The relatively short operational life of flexible skirt/seal components, such as fingers, not only limits the full military utilization of this technology, but also significantly increases the cost of maintenance. For example, the entire skirt system for a 60-ton ACV was approximately $500,000 in 1975. The craft has about 120 fingers and their average life is 300 hours. In 2000 hours of operation, the equivalent of 8 complete sets of fingers would be used. At a conservative estimate of $300 per finger, the replacement cost is $252,000, or slightly more than one-half of the initial cost of the total skirt system. In addition, nearly 4000 man hours of labor are required for removal and installation of these fingers.

While costs of this magnitude make the military utilization of surface effect vehicles very marginal, modest improvements in finger life can significantly change this outlook.

1.3 Committee Objectives

This task, one of a series of DoD studies by the National Materials Advisory Board (NMAB), falls under the terms of the existing contract with the Department of Defense and National Aeronautics and Space Administration (DoD/NASA Contract No. MDA 903-74-C0167).

The short life of skirts fabricated from fabric reinforced elastomeric composites limits the military potential and commercial practicality of the SEV mode of transportation. Even shorter skirt lives are anticipated for the larger, higher speed vehicles under development. To determine the reasons for rapid skirt deterioration and to identify approaches for the development of skirts with increased lives, the committee set forth the following objectives:

1. Assess the state-of-the-art and evaluate work currently being undertaken with respect to:

   a. Fibers, elastomers, and adhesives.

   b. Construction of composites, including interaction of the elements of the composite.

   c. Fabrication of composites and components made therefrom.

   d. Laboratory evaluations of composite materials; statistical design of tests; correlation with large scale performance; principal modes of failure; failure analysis.

2. Identify the loading conditions and environmental factors that influence the service life of skirt and seal materials.

3. a. Examine and recommend laboratory scale evaluation techniques, involving statistically designed experiments and interpretation, correlatable with field service results.

   b. Recommend procedures for service testing of fingers fabricated from promising candidate composites.

4. Consider modeling techniques to be used in lieu of full scale testing.

5. Identify those characteristics of the materials that will promote increased service life.

6. Suggest new materials, constructions, and novel fabrication techniques that might yield improved composites and components.

1.3.1 Exclusions

Certain topics were excluded from the committee objectives to avoid a dilution of the main effort within the time span and monetary allotment for the study. These exclusions are:

1. Field service repair of damaged skirt/seal systems.

2. Finger design other than the extent that it couples with materials choice.

3. Ballistic effects on skirt/seal materials.

4. Mechanical attachments used to join skirt/seal systems to the vehicle hard structure, other than to the extent that they affect the actual skirt/seal materials selection.

1.4 Committee Approach to Problem

1.4.1 Composition of the Committee

The membership of the committee is presented on page v. The personnel were chosen so that representative areas of expertise needed for the resolution of the problem were incorporated. Broadly enumerated, the problem encompasses polymeric materials, failure phenomena, testing, and design.

1.4.2 Familiarization with Problem

The Navy liaison representative to the committee gave a general tutorial presentation at the initial meeting in which air cushion technology as applied to air cushion vehicles and surface effect ships was discussed. The topics covered were:

1. Statement of the problem as the Navy views it.
2. Description of surface effect vehicles.
3. Lift system operation.
4. Seal and skirt system description.
5. The environmental and operational requirements.
6. Material descriptions.
7. Skirt/seal loads.
8. Problems and limitations of materials.
9. Materials testing and evaluation.
10. Materials employed or contemplated.

11. Results and data.

12. Information sources.

13. Charge to the committee.

Although the Department of the Navy is the principal sponsor of this task, in order to maximize the benefits derived from the study, the Department of the Army and the Department of the Air Force participated and their liaison representatives presented their respective agencies' interests in craft based on air cushion technology. The Army representative discussed two projects, the stretched version of the Voyageur (LACV-30) and an air cushion barge. The liaison representative from the Air Force described his service's experiences with the aircraft air cushion landing system.

In addition, the committee was addressed by a representative of the Canadian government who related the Canadian experiences with the Voyageur and air cushion landing program, the latter being a joint effort between the USAF and the Canadian government. Canada is also interested in other air cushion vehicle applications e.g. icebreaking, use of rafts of various types for transportation overland and in the arctic.

For background material to assess the state-of-the-art and work in progress, the committee members extensively examined technical reports suggested by the liaison representatives and references derived from these reports. Many of these are cited as references throughout the report. A computer search for articles relevant to skirt and seal materials used in surface effect craft was requested of The Maritime Research Information Service of the Transportation Research Board of the National Academy of Sciences. Abstracts of articles on this topic were received and, where appropriate, the original reports were ordered and examined.

The committee visited the facilities of four industrial DoD contractors; two (Goodyear Tire and Rubber Co. and the B.F.Goodrich Co.) being material suppliers and two (Aerojet-General Corp. and Bell Aerospace Corp.) builders of air cushion craft for the Navy and Army. Tutorials were presented, the facilities and actual craft hardware were viewed, and committee members posed questions to obtain technical input.

Further technical information was obtained during a visit by a committee member to British Hovercraft Inc., an overseas SEV manufacturer, and by having DuPont technical consultants on fabric coating appear before the committee.

1.5 The Committee's Report

The essential features of the report comprise chapters on a) the materials, viz. fibers and fabrics therefrom, elastomers, adhesives, that are assembled into b) the composite, which is c) fabricated into a skirt system. The d) mechanical properties and failure modes, and e) test methods chapters complement the materials, composite, and skirt system sections.

For each of these topics, consideration was given to the state-of-the-art, work in progress, and the gaps in knowledge. Conclusions and subsequent recommendations are reported and the possible benefits to be derived from following the latter are postulated.

CHAPTER 2

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

The main conclusions and recommendations developed in the report are summarized below. They result from the more detailed discussions in Chapters 3 through 8, which should be consulted for both supporting evidence and the general context in which the conclusions and recommendations should be viewed.

2.1 Conclusions

The life of the elastomer-coated fabric bag portion of the ACV skirt system is adequate. However, the lives of the lower, finger portion of the ACV skirt system and the lower segments of SES seals are short. It is anticipated that even shorter skirt* lives will be encountered with the larger, higher speed vehicles under development.

The reasons for the short skirt lives are given in the following conclusions:

1. There has been insufficient emphasis in SEV programs on skirt materials development. A comprehensive, integrated program with a sustained materials development task has not been undertaken.

2. There is a serious lack of field evaluation data to correlate with laboratory tests. The limited full-scale performance data available does not permit statistically significant conclusions to be formulated.

3. Little is known in detail about the nature of the failure processes. Multiple modes of failure have been noted, depending on vehicle and skirt design, loading, temperature, envionrment, and material. Thus there may not be a single best material for all operating conditions, vehicle types and sizes, and skirt designs. More information is needed to permit adequate modeling and scaling.

4. No laboratory tests that adequately predict the performance of skirt materials have been developed. Consequently a unified materials design/selection methodology has yet to be established.

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* "Skirt" hereafter refers to both the peripheral seal system for air cushion vehicles (ACV's) and the bow and stern seals for surface effect ships (SES's).

5. The results of the various development and testing programs are difficult to correlate with each other. Materials selection criteria, composition and manufacturing process parameters are insufficiently documented in the various reports.

6. The effects on service performance of several important material and physical properties have yet to be definitively evaluated. Fiber choice, level of coating adhesion, coated fabric stiffness, and long-term water immersion, etc. have not been exhaustively studied for their influence on skirt life.

7. Load magnitudes and loading profiles have yet to be completely established. This deficiency makes it difficult to develop a design methodology.

8. There has been no emphasis on the innovative use of new engineering materials, structures, and manufacturing processes. Most SEV development programs have utilized only off-the-shelf materials thereby restricting the range of selection of material types.

2.2 Recommendations

The above conclusions lead to the following recommendations for a course of action that the committee believes will result in the development of skirt systems with improved service life.

1. Designate a single organization with responsibility for the coordination of SEV programs. Their mission would be to monitor:

a) data on all skirt materials;

b) laboratory testing;

c) field service evaluation.

The team given this assignment should be composed of a manager and at least two senior engineers. Sufficient funds should be provided to permit them to get out into the field and collect, analyze, correlate, and communicate data being developed on all SEV programs. Their activity will permit more meaningful comparisons of data, facilitate exchange of information among interested groups, minimize duplication of effort, and ensure that all potential material systems are evaluated.

2. Undertake a continuing and sustained product improvement program. This effort should take into

consideration what is known of current technology in the field. It could include appropriate:

a) fiber types;

b) fabric constructions;

c) adhesives;

d) coating materials, including all recipe components;

e) manufacturing processes and process parameters.

A full range of standard laboratory tests and available simulated end-use tests should be conducted on all candidate materials, making appropriate choices of test parameters.

The committee believes that this effort could result in a two-fold increase in skirt life.

3. Investigate innovative concepts for skirt systems. This effort should include both novel materials' systems and new seal designs. The Committee believes that this approach must be pursued if an improvement in current skirt life by more than a factor of two is to be achieved. An analogy might be the enhancement in life realized by changing from the highly developed bias-ply automobile tire to the radial tire.

4. Obtain full documentation for all skirt materials evaluated. This should include materials' compositions and manufacturing process parameters. To do so will permit more meaningful comparison of various researchers' data, enable materials to be reproduced, and reduce program overlap. It may also indicate more clearly directions for product improvement.

5. Acquire reliable skirt performance data from vehicles in service. The investigation should include:

a) recording of mission profiles;

b) periodic examination of wear rates on skirts;

c) failure analysis of degraded or worn areas.

Correlation and analysis of service performance with environment, laboratory test data, and material characteristics will lead to a more fundamental understanding of the interrelationship of the materials and their environment.

If adequate cooperation of vehicle operators can not be obtained to permit the acquisition of meaningful field data, the committee recommends that consideration be given to utilizing an appropriate type and size vehicle dedicated to service evaluation of skirt materials. This would permit full control of service profile and might accelerate the evaluation of candidate materials.

6. Increase efforts to instrument skirts of service vehicles. This would permit obtaining more information on stresses, loads, and temperatures in the materials.

7. Initiate a load prediction program. The results of the program would facilitate the successful design of future, high-performance SEV's.

CHAPTER 3

FAILURE MODES: EFFECTS OF LOADING AND ENVIRONMENT

3.1 Introduction

This chapter discusses the various modes of failure experienced by skirts based on finger designs as related to the types of loading and the environment. Table 3-1 summarizes the loads involved in the different component functions and indicates the corresponding material requirements. Table 3-2 summarizes principal failure processes observed for skirts on several vehicles (Bell Aerospace Corporation, 1977).

3.2 Analysis of Data

3.2.1 Modes of Failure

Examination of the extensive literature associated with past and current development programs indicates that three major causes of failure appear to be prevalent in skirt materials: delamination, abrasion, and tearing in tension. These are discussed below and outlined in Figure 3-1 along with major factors which can influence the types and degree of failures.

Flex-cracking of the rubber coating may occur prior to the failure of the reinforced fabric. Occurrence of such cracking per se does not constitute failure, and does not necessarily impair performance, but may be an early step in the failure process.

3.2.1.1 Delamination

Delamination* failure in skirts is the subject of some controversy with respect to surface effect vehicles. On the one hand the so-called "heavy skirt" school of design, exemplified by the British Hovercraft Corporation, 1973, believes that due to the nature of a typical operational profile of their craft, and also due to the design of their skirt system, high frequency oscillation at the skirt tips

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* In this report, "delamination" refers to separation of the coating from the substrate. As observed visually, delamination occurs nominally at the interface. However, in a <u>microscopic</u> sense, it is not always known whether the locus of failure is <u>precisely</u> at the fiber-adhesive or adhesive-rubber interface, within the adhesive, or just beyond the rubber surface.

Table 3 - 1

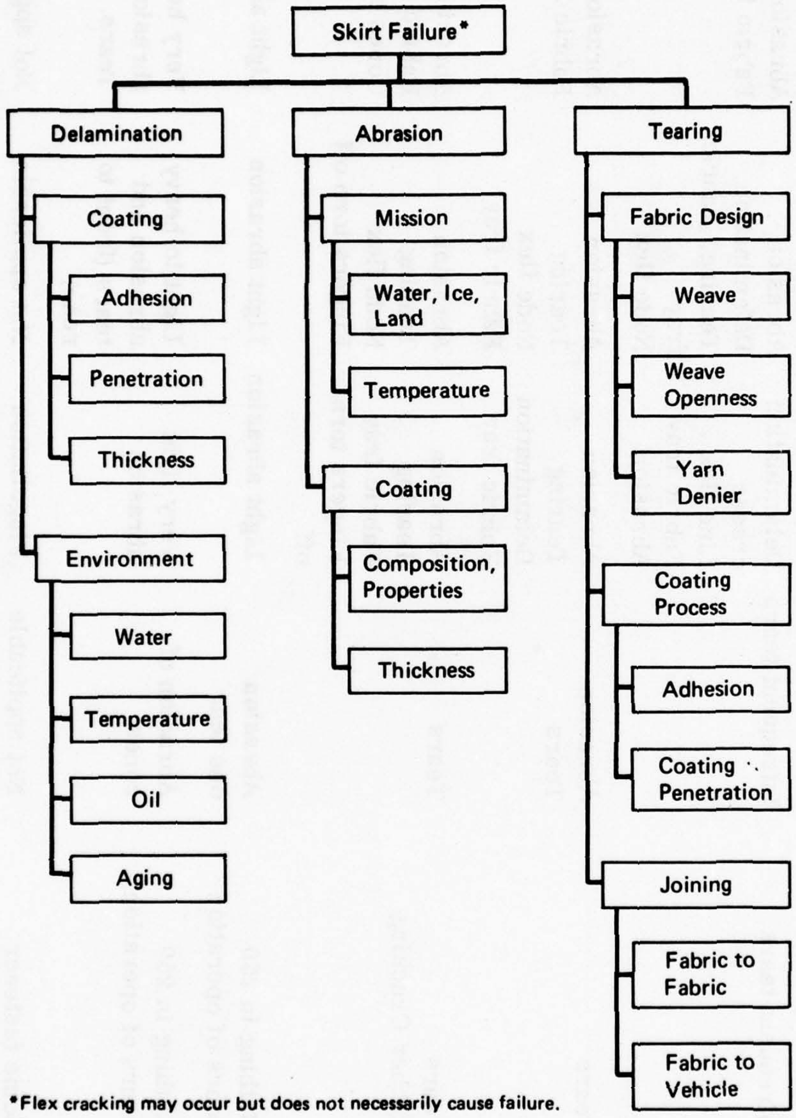
SUMMARY OF LOADS EXPERIENCED BY BAGS AND FINGERS

Element	Purpose	Primary Load Environment	Primary Material Requirements
Bag	• Distribute air uniformly to cushion	• Biaxial pressure stresses	• Sufficiently flexible over given operational temp. range (low stiffness)
	• Retain sufficient flexibility to clear hard structure over obstacles (land, waves, etc.)	• Occasional (low frequency) impact loading	• Biaxial (orthotropic strength)
			• Tear resistant
			• Resistant to degradation due to atmospheric and environmental effects
Finger (or contact seal component)	• Contain cushion pressure	• Constant dynamic oscillating/impact loading	• Flexural fatigue strength and life
	• Retain sufficient flexibility to clear obstacles without excessive loss of cushion air	• Abrasion	• Abrasion resistant
			• Tear resistant
			• Resistant to degradation due to atmospheric/environmental effects

Table 3 - 2

DOMINANT SKIRT FAILURE PROCESSES FOR VARIOUS VEHICLES (BELL AEROSPACE CORP., 1977)

Vehicle	Outer Bags	Stability Bags	Bow Fingers	Side Fingers	Rear Cones
SR. N4 Cross Channel Ferry	Infrequent tears	Infrequent tears	Delamination crease Line flex Fabric fray Abrasion	Abrasion Delamination Tearing, Fabric fray Node flex	Abrasion Fabric fray
Voyageur Canadian Coast Guard Ice Breaking	Tears	Abrasion Tears	Abrasion Tearing Delamination Fabric fray	Abrasion Tearing Node flex Fabric fray	Abrasion Fabric fray
Voyageur Artic Operations	Tears Rubber Cracking	Tears	Abrasion Tearing Fabric fray Fingers torn off	Abrasion Tearing Node flex Fingers torn off	Abrasion Fabric fray Cones torn off
LACV-30-1	Nothing in 250 hours of operation	Abrasion one tear	Light abrasion	Light abrasion	Light abrasion
LACV-30-2 Vehicle Trimmed Bow-Up	Nothing in 250 hours of operation	Abrasion of cones	Very light abrasion	Light to heavy abrasion and tears (front to rear)	Very heavy abrasion Tears
SES-100B	Some fastener abrasion, Seam delamination, Rubber cracking	Not applicable	Flagellation Rubber cracking Fabric fray	Not applicable	Not applicable



*Flex cracking may occur but does not necessarily cause failure.

FIGURE 3-1 Principal failure types in skirts and major factors involved.

causes delamination failure to be the primary source of material degradation. The BHC group maintains that both edge fraying and buckling are basically delamination failures, since in all cases the failure begins by separation of the polymer coat from the fabric base. Following this the polymer coat fractures, exposing the fabric base to water and substantially reducing its bending stiffness. From that point on, failure is rapid since preferential bending takes place in those regions where the coat is separated from the fabric base and early fatigue failure occurs.

Alternately, the so-called "light skirt" school of thought, exemplified by Vosper Thornycroft, 1973, maintains that under different types of operational conditions and skirt designs, where the skirt tends to contact the surface of the earth or sea more frequently, high-frequency flutter or vibration of the skirt edges is prevented by the contact forces so that delamination is not as prevalent. This seems to imply that other forms of wear, such as direct abrasion, would be more important in this type of design.

3.2.1.2 Abrasion/erosion

Abrasion or erosion may be a serious problem for skirt materials in service under a wide variety of conditions ranging from friction against seawater to friction against sand, gravel, or concrete. Indeed, such material degradation has been seen in actual operation. This, coupled with the delamination described in the previous section, probably constitutes the major cause of the edge-fraying often observed on operating skirt systems in present-day craft. Self-abrasion is also possible if the coating rubs against itself, or against mechanical fasteners.

3.2.1.3 Tear Failures

Instances have been reported in which the mode of failure is tearing* (Aerojet General Corporation, 1976).

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* It should be noted that two tear mechanisms may be observed, depending on whether or not the initial hole is formed before or after pressurization. If before, quite high loads can be attained before fracture; if after, crack propagation may occur at <u>low</u> loads. However, the ranking of materials should be the same in each case (Freeston and Claus, 1973).

This type of failure is commonly encountered in bag and finger elements where pressurization loads exist and the fabric must act in a structural sense in order to contain the pressure. Under these conditions substantial strain energy is stored in the stressed structure, and a tear or rip, once initiated, is often propagated over a long distance. This type of failure may occur due either to accidental impact during operation, or to stress concentrations associated with feed holes in the bag or trunk, or with attachment points. In all cases the general property of the fabric which seems to be most useful in evaluating such failure is tear resistance as measured by tear tests.

In any case, failures have been examined only visually or at low magnification.

3.2.2 Loading Conditions

Clearly, loading conditions comprise a complex system of static and dynamic loads associated with a wide range of loading rates and frequencies and dependent on the function and location of the element concerned (see for example, Wheeler, 1974). The forces involved may be classified in three groups: pressure, vibration, and contact (see Figure 3-2). (For implications in design, see section 6.1).

3.2.2.1 Pressure Forces

Probably the major set of forces which must be considered in bag design are pressure-vessel forces associated with ducting the pressurized air to the individual fingers. This is commonly done through a bag or trunk design (usually of essentially cylindrical shape) and placed around the perimeter of the craft. Feed holes in this cylindrical duct lead to the individual fingers of cells. In view of the fact that the basic load here is the internal pressure, and that the shape is cylindrical, then it may be said that this type of structure lends itself more readily to conventional structural analysis than do the fingers themselves. In this particular case it would be anticipated that general stress analysis techniques could be used. Such trunks or bags are also subject to additional loadings which are not as well defined as the basic pressure forces. These loadings result from impacts with waves or with foreign objects or ice ridges.

Although some analytical methods have been used, they are usually based on static loading and require large factors of safety applied to the inherent strengths of the trunk materials. While this process may be workable, it often leads to difficulties at points of high stress concentration, such as feed holes or attachment points,

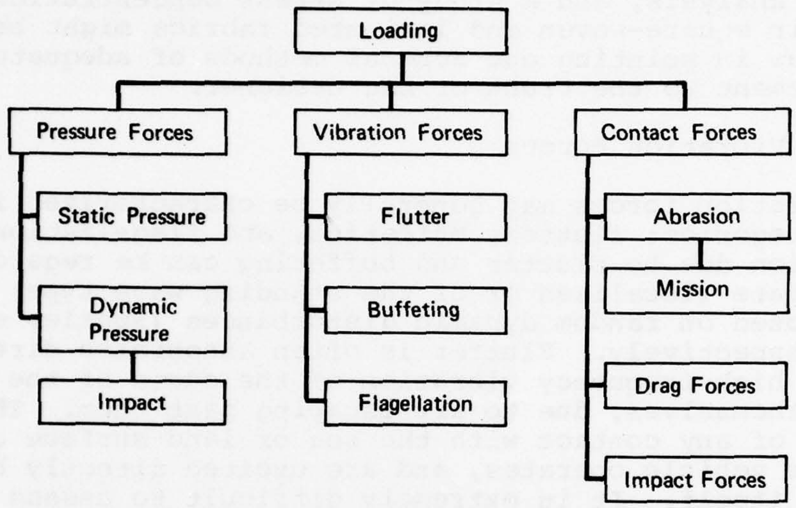

FIGURE 3-2 Forces involved in skirt loading.

since here the stress concentration effects are multiplied by impact loads. Compounding these factors is the role of the orthotropic materials involved, which often are less tolerant of stress concentration effects than the normal isotropic materials with which most designers are more familiar. The situation is one which lends itself in some cases to analysis, and a study of stress concentration effects in square-woven and laminated fabrics might be of some value in pointing out general methods of adequate reinforcement to the trunk or bag designer.

3.2.2.2 Vibration Forces

Vibration forces may generally be characterized in three categories: flutter, buffeting, and flagellation. Oscillation due to flutter and buffeting can be regarded as steady-state (localized or of the standing wave type) motion superimposed on random dynamic disturbances (Buckley et al., 1973), respectively. Flutter is often associated directly with the high-frequency vibration of the edges of the fingers themselves, due to air escaping past them. These are free of any contact with the sea or land surface over which the vehicle operates, and are excited directly by the air flow itself. It is extremely difficult to assess the magnitudes of such forces, particularly in any manner which lends itself to analytical treatment. The magnitudes of cyclic bending moments or tension forces are simply not known well enough in such situations. As a matter of fact, the design characteristics of the finger which influence the magnitude of such forces are not well understood.

A second major cause of such forces is flagellation associated with contact of a finger edge with either a wave or some obstacle on land. The resulting spring-back and low-frequency oscillation of the finger, due to the pressure forces driving it back into an equilibrium position, provide stresses and moments which in some cases are sufficient to cause material degradation and failure. Again these are not well understood, and the main efforts to date have been centered around attempting to reproduce such effects in the laboratory by use of test devices involving obstacles or beaters (see Chapter 7). At the present time the adequacy of these tests is uncertain, and yet the subject is certainly important to operation over ice, land, or water.

In general it is suggested that both flutter and flagellation forces probably lead primarily to delamination processes in most of the materials currently in service, and in most contemplated for future service. However, verification of this point would require further comparison of field data with laboratory experiment.

3.2.2.3 Contact Forces

Abrasion/erosion

One of the two more common forms of contact forces is direct abrasion against relatively rigid materials such as soil or ice. There is strong feeling that abrasion can be a serious problem, particularly in regard to arctic operations. Although there is an enormous amount of literature on the abrasion of rubber as related to tires (as detailed for instance in Rubber Chemistry and Technology) there seems to be a relatively small amount of information on this type of wear in SEV systems. Available photographs (Aerojet General Corporation, 1976) show forms of abrasive wear which seem to be of the same general type as those investigated experimentally by direct contact experiments recently undertaken (Tennyson and Smailys, 1977). (See also Section 3.2.5.1). However, so far material selection has not seemed to take this factor into account as much as other factors more commonly associated with sea operation. Little information is available on the performance of conventional SEV skirt materials in abrasive conditions such as encountered over land service.

While contact with the terrain is probably the major source of abrasion, any contact of rubber surfaces with themselves or with attachments could constitute a secondary cause of degradation.

Erosion must also be considered as a possible mechanism, though direct evidence for it has not yet been adduced. However, one would expect performance rankings to be the same as for abrasion.

Drag Forces

Drag forces can be broken down into two general types characteristic of operation in calm or rough water. In the first, calm water forces involve contact of the finger edges with water as the craft moves. Similar contact takes place on land. Generally these forces are small in total magnitude but can be locally high at the finger edges. To some extent such forces are a function of skirt mass. They can cause tearing in local areas or cracking of the surface. Some evidence of this kind of failure appears but it does not seem to be a serious problem at present.

From the overall structural point of view, rough water drag forces appear to be more serious. Here such things as scooping of water or nose-down wave impact can cause large transient hydrodynamic forces in the skirt system. These are distributed over fairly large areas of the skirt and can result in tearing of the skirt assembly over significant lengths. These are forces of major magnitude and normally should be taken into account in the initial structural design of the skirt and trunk system. In a sense they may be considered analogous to the forces considered in designing for gust loads in aircraft practice, in that they are not a normal part of the operating structural loads but must be accounted for on a worst-case basis or on a structural frequency basis as additional design loads. Unfortunately, the distribution of the loads is not known precisely.

Impact Forces

It is possible for the craft to experience impact forces either due to objects floating in the water or due to unexpected land obstructions. While impact forces can probably be estimated reasonably well, their distribution is not known, and, in any case, their influence on structural design has so far been apparently neglected, though considerable laboratory testing has been done with belt and rod impactors to simulate conditions in the field (see Section 7.4.3). However, correlation of laboratory and field tests has been severely limited by the lack of field service data.

3.2.2.4 Loading Rates, Frequencies, and Wave Forms

While the effects of loading rates on the behavior of polymers is now generally recognized as important in static loading conditions, effects of frequency and wave form are seldom considered when loading is cyclic, that is, in fatigue. At the same time, changes in the wave form and frequency of a cyclic load can have dramatic effects on the rate of fatigue crack growth in polymers in general, including elastomers (Hertzberg et al., 1975). For a given time under load, a square wave will exhibit a much higher strain-rate and integrated load-time product than a sinusoidal wave; similarly ramp-type loads will differ depending on the rate of load-rise. Clearly for a given wave form, the loading rate will depend on the frequency. Some materials are most sensitive to time under load, some to frequency, and some to wave form.

In addition (see Section 3.2.5.1) (Ferry, 1970, and Hertzberg, et. al., 1975), frequency also affects the rate of hysteretic heating. In an unnotched specimen of given dimensions undergoing fatigue

$$\frac{dT}{dt} = f[\omega, \sigma, J''(\omega), \kappa] \quad ,$$

where $\frac{dT}{dt}$ is the rate of temperature rise throughout the specimen, ω the frequency, σ the maximum load, $J''(\omega)$ the loss compliance, and κ the thermal diffusivity. Thus, other things being equal, the higher the frequency, the higher the rate of temperature rise. If $J''(\omega)$ is independent of temperature, a steady state will be reached in which the temperature rise is balanced by thermal losses to the environment. If $J''(\omega)$ increases with temperature in the range concerned, then the rate of temperature rise can accelerate and thermally induced damage results. Such a situation occurs both in homogeneous polymers and in composite systems such as tires. On the other hand, cooling of a vibrating specimen can reduce the rate of heating and hence fatigue damage. Thus with a skirt in water, temperature rises will be limited by heat transfer to the water; however quantitative information is not available. It may also be noted that adiabatic heating localized at a crack tip may in some cases result in creep and consequent blunting of the crack.

Clearly, then, the effects of frequency are complex and depend on the type of material response, on whether the load is applied throughout a specimen or concentrated at a flaw, and on the rate of heat transfer to the environment. Hence, one cannot legitimately take measurements of fatigue life at one frequency and deduce fatigue lives at other frequencies, unless it is known otherwise from experiment.

3.2.3 Stress Analysis of Coated Fabrics

In general, one can regard elastomer-coated fabrics as nonlinear, anisotropic, viscoelastic materials in terms of their stress-strain behaviour. This type of response is characterized by a lack of symmetry in material properties, that is, deformation is a function of the direction of loading, strain-rate sensitivity, and dependent on prior load history such as on the existence of pre-load in the material. Confronted with these difficulties, the engineer is seriously restricted in any attempt to perform a credible stress analysis on an inflated skirt structure subject to either static or dynamic loads, particularly if adequate material characterization data are lacking.

However, for many coated fabrics, nominally linear behaviour is observed when the loads are slowly varied. If, then, viscoelastic behaviour is neglected and one assumes a plane-stress state (which should model a skirt or finger structure reasonably well), the generalized two-dimensional form of Hooke's law can be used as the constitutive relation.

Again, difficulties arise when anisotropic material properties are required because each of the nine terms in the compliance (or stiffness) matrix would have to be determined experimentally. On the other hand, if some form of material symmetry exists, as is the case for an orthotropic (cross-ply) fabric sandwiched between isotropic, homogeneous elastomer coatings, then the compliance matrix can be reduced to four independent parameters (Alley and Faison, 1972a, 1972b). Experimental tests on material samples satisfying the orthotropic model description can be performed utilizing standard shear, tension, and biaxial loading to yield these material properties. The major problem associated with these measurements is that of obtaining reliable strain data (Buckley et al., 1973).

For dynamic loading, an approximate analysis can be made by measuring the strain-rate sensitivity of the above parameters. However, this information alone will not provide insight into viscoelastic damping and hysteresis effects which are important considerations if one wishes to analyze the oscillation of finger structures which are sensitive to frequency as well as to strain-rate.

One of the major gaps in knowledge associated with the materials currently utilized in SEV skirts is the methodology by which one obtains reliable measurements of the material property coefficients. As noted earlier, it has been observed that, for certain materials, the stress-strain behavior can change depending upon whether preload exists and how the loads are applied (for example, biaxial vs. uniaxial tests). Other areas deserving serious attention include rate-dependence measurements on the stiffness coefficients and nonlinear modeling of materials including viscoelastic characterization (see also Chapter 7).

3.2.4 Effects of Skirt Design

As mentioned in Section 1.1, several design philosophies exist:

British Hovercraft Corporation - heavy material

Vosper Thornycroft - light material, segmented

Aerojet-General - pericell

French organizations - Bertin skirt (jupe)

At present, it seems impossible to reach definitive conclusions about the effects of skirt design on the mode of failure and about the interaction between the material per se and the design. Clearly these effects must also reflect the operational profile of a particular craft. As mentioned above, some designers believe that a heavy-skirt design may be more appropriate when contact with land or water is nominal and a light-skirt design when such contact is more frequent. Failure by delamination and abrasion may be expected to be dominant in the heavy- and light-skirt designs, respectively.

3.2.5 Effects of Environment

As is the case with loading conditions, the environment encountered is complex, and may be expected to interact with the loads. Moreover, effects of the interaction will be different for the various components in a fabric and for different positions of fingers on the craft. Principal environmental factors include the following: temperature, fuel, oil, water, other chemicals, and aging due to ultraviolet radiation and ozone.

3.2.5.1 Temperature

Temperature certainly has a major effect on the mechanical response of a polymeric composite. Usually wear and degradation of all kinds are greater the higher the temperature. It should also be noted that the temperature concerned is that of the specimen, and this may or may not correspond to the ambient value. In cyclic loading, specimen temperature, which depends on the internal damping factor, stress, frequency, and heat transfer characteristics, may rise due to hysteretic heating. It is not known how important this fact is to skirts and seals (see Section 3.2.2.4).

Some laboratory studies do confirm the effect of temperature mentioned. Thus, the rate of abrasive wear of a typical skirt material has been shown to be invariably higher, the higher the temperature (Tennyson and Smailys, 1977). While the rate of wear decreased with time, it was much greater at 75°F than at -30°F. Hence, in terms of abrasion per se, materials suitable for use in warm waters may be expected to be also suitable in arctic conditions; the converse will, however, not necessarily be true. Temperature may also affect the mechanism of abrasion. At high temperatures (in air), adiabatic heating may ensure that the rubber coating is in the rubbery state and thus lead to failure by "rolling" (stretching followed by tearing at right angles to the applied stress). In contrast, at temperatures low enough that the rubber is stiff, failure will tend to be by simple abrasion. Unfortunately, the effect of immersion in water is not known.

With respect to fatigue or static failure, again high temperatures should generally tend to be more damaging than low ones (Andrews, 1968). Hysteretic heating may also occur during flexing, and has been observed in some cases with skirt materials (Goodyear Aerospace Corporation, 1974). Such heating will be greater the higher the load, frequency, and loss compliance of the material (Section 3.2.2.4).

3.2.5.2 Water and Other Chemicals

With some exceptions, water tends to have a deleterious effect on the mechanical performance of polymers. In fact, contractors have examined the effects of water on routine tests such as flagellation and tensile strength (Boeing Company, 1974; Kelly et al., 1974; B. F. Goodrich Company, 1976). Effects of hydrocarbons such as JP-4 fuel have been studied as well.

3.2.5.3 Aging

As with water, tests have been conducted to determine the effect of aging due to oxidation and sunlight. Such aging is familiar to most people who have used ordinary rubber articles such as tires, and is ranked by one contractor as a secondary cause of failure, following mechanical and abrasive failure (B. F. Goodrich Company, 1976).

3.2.6 Data Correlations

Here, most studies have involved laboratory tests, especially with flagellators and impactors, on the assumption that these tests should correlate with service performance. Indeed, some correlations exist between the material properties and performance in such simulated tests. For example, criteria for good flagellation behavior have been expressed in terms of: Young's modulus, strain energy, hardness, and tear strength (Hochrein and Thiruvengadam, 1974).

Some correlations of service life have also been obtained with flagellation loss rates, tear strength, fabric mass, thickness, and coefficient of friction (Swallow et al., 1971).

Without further service life tests, it is impossible to go beyond these limited, though interesting, correlations.

3.3 Gaps in Knowledge

1. The failure processes themselves are not well enough understood, specifically, the locus (in delamination), and the criteria for the initiation and propagation of cracks, as a function of material, loading, and environment.

2. Relatively little stress analysis for various designs and loading is available.

3. Not enough is known about the materials themselves, about behavior in service, or about which tests correlate best with service conditions.

3.4 Conclusions

Based on the examination of the information available, some general conclusions may be drawn:

1. Multiple modes of failure exist, depending on design, loading, temperature, and material. Thus there may not be a single "best" material for all conditions. Further, little is known in detail about the nature of the failure processes themselves, and about criteria for failure in terms of current concepts of fracture mechanics. Many failures are seen to occur as a result of repeated loads, that is, under fatigue loading conditions.

2. The various studies are difficult to correlate with each other for several reasons: diverse test techniques, ill-defined materials, frequent lack of statistically significant data. Nevertheless, some trends and correlations can be discerned.

3. There is a serious lack of field evaluation which is necessary for correlation with laboratory tests.

4. Hence, objective and general criteria for materials selection cannot now be specified.

3.5 Recommendations

1. Clearly quantitative data on service life as a function of operating conditions and environment are needed. Individual service studies should be controlled experiments under constant conditions, i.e., controlled and constant mission profiles.

2. More detailed knowledge of the locus of failure (in delamination) and of the rate of the failure process should be obtained, perhaps using scanning electron microscopy to characterize the fracture surfaces, and fracture mechanics concepts to characterize the rates and criteria for failure, as functions of wave form, frequency, and environmental conditions.

3. Once these correlations are better known, additional data on the effects of temperature, frequency, and other factors in a service profile will be useful.

4. While it is difficult to analyze some factors, e.g., pressure loads in fingers, and the magnitude of vibration forces, stress analysis for static, pseudodynamic and dynamic loading should be attempted. When necessary, data should be estimated for the worst possible cases. In particular, analysis of stress concentrations in various kinds of fabric, of how skirt design affects impact forces and fatigue behavior, and of drag forces in deep water should be feasible and useful. Better modeling of wave-form and frequency for the loads would be desirable.

5. In the studies recommended, several points should be emphasized. First, stress analysis should be highly coordinated with laboratory and service tests. Second, testing should obviously be concentrated on the most suitable properties for screening once they are known with reasonable assurance. Third, the composition of the materials used should be known.

CHAPTER 4

SKIRTS AND SEAL MATERIALS

4.1 General Construction Considerations

Skirts and seals on SEV's to date are composites in the form of a woven fabric embedded in an elastomer matrix. As currently conceived the fabric plays several roles: it reinforces the elastomer, and gives the skirt shape, geometric stability, impact strength, fatigue resistance and load-carrying capacity. The elastomer provides impermeability to air for sealing, abrasion and erosion resistance, impact cushioning, and stiffness. The matrix also transmits the applied loads to the reinforcing filaments through shearing of the elastomer.

An adhesive is usually applied to the fabric prior to elastomer coating to effect a strong bond at the interface and prevent wicking of water. Although the adhesive corresponds to less than one percent by weight of the total composite, it has a major effect on skirt performance.

The rationale for use of such a composite for SEV skirts is that it can have properties that cannot be achieved with any of the components acting alone. However, it must be recognized that the optimum configuration will depend on the skirt and vehicle design, and vehicle mission.

The component properties believed to be essential, candidate materials, and construction variables and their effects are discussed below. Design parameters for the coated fabric are outlined in Figure 4-1. The state of the art is reported and gaps in knowledge identified together with conclusions and recommendations.

4.2 Fabric

Conventional flat woven fabric consists of two sets of orthogonal bundles of polymeric filaments, known as yarns, interlaced in a regular pattern. The properties of the fabric can be varied by altering the pattern in which the yarns are interlaced, the number of yarns per unit width of fabric, the size of the yarns, the size of the fibers in the yarn, the extent to which the fibers are twisted together and the fiber used. The degree of fabric property imbalance can also be controlled by varying the ratio of the number of

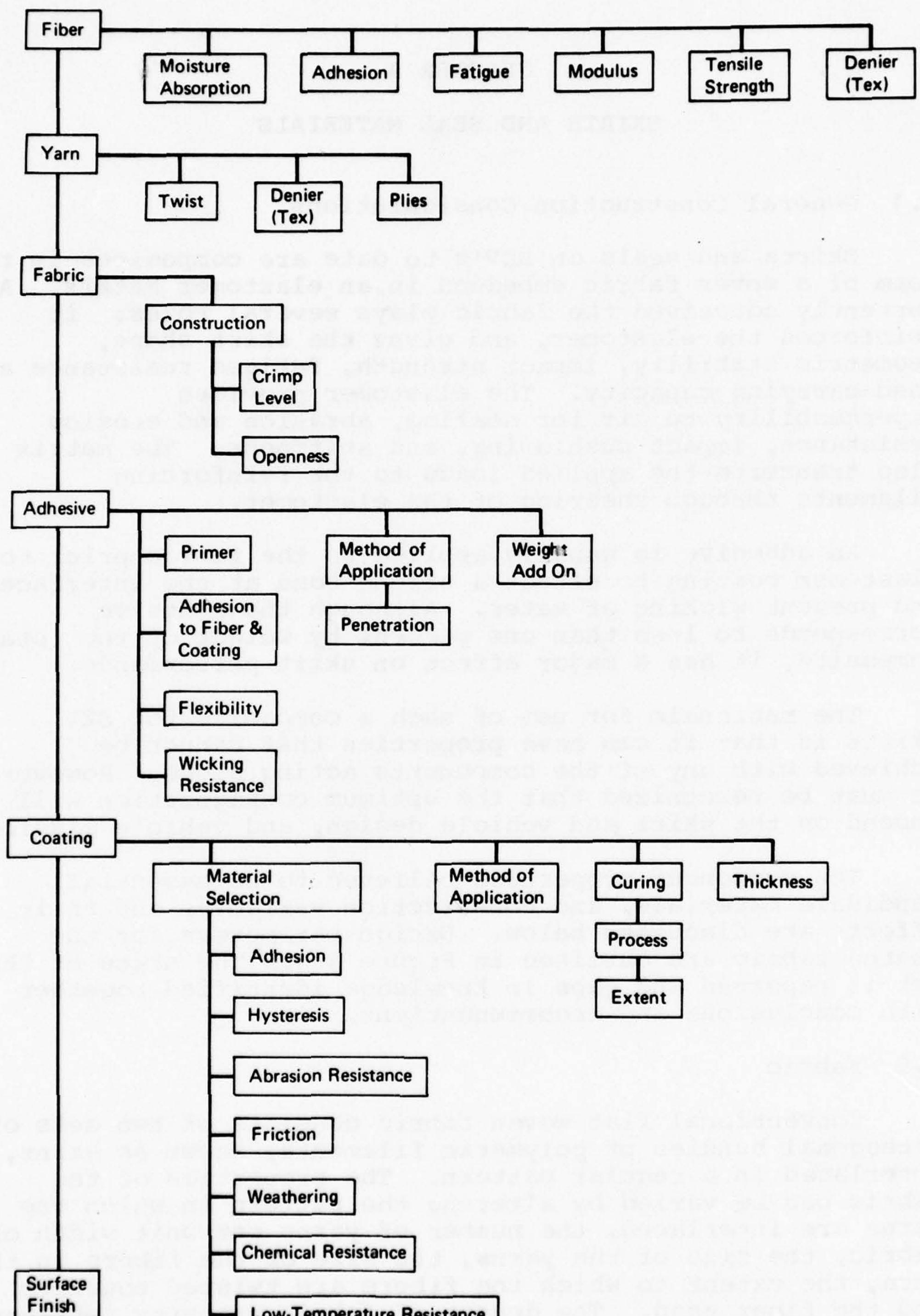

FIGURE 4-1 Coated fabric design parameters.

yarns to the yarn denier (Tex)* in the two orthogonal directions. All of these parameters give the designer great freedom in fabricating a composite with specific properties.

Contour woven fabric might also be utilized for a skirt and seal reinforcement. This material comprises two sets of yarns woven into three dimensional surfaces by dropping and adding warp yarns.

Triaxial woven fabric is also available for consideration as a skirt reinforcement. It is comprised of three sets of yarns interwoven at 60° to each other. This type of fabric exhibits high resistance to tearing and high in-plane shear stiffness.

Unidirectional fabric, e.g., tire cord fabric, is also available. This type of fabric consists of a parallel array of yarns held together by a small-denier filling yarn woven approximately every inch. To reinforce a skirt, two or more of these fabrics would be laminated together at an angle to each other.

4.2.1 Fibers

4.2.1.1 Available Fibers

A wide range of materials are commercially produced as fibers including glass, steel, and synthetic polymers such as polyesters, aliphatic and aromatic polyamides, polyolefins, polyurethanes, polyacrylonitrile, and a crosslinked poly(vinyl alcohol) made in Japan. In addition natural fibers such as cotton and wool are available, as are regenerated cellulosic fibers (rayon). The textile yarns to be woven into fabrics for skirts are believed to require high modulus, moisture resistance, and fatigue resistance. In arctic applications, they require the ability to retain flexural strength at low temperatures. The advantages and disadvantages of candidate fibers are summarized in Table 4-1.

It should be noted that large variations in fiber properties can be brought about by changes in fabrication conditions. Such varying conditions include the type of spinning process (melt, wet, dry) and the details of subsequent drawing and annealing. The same polypropylene may, by high speed melt spinning and annealing, be made into a highly flexible fiber, but, by slow spinning from the melt

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* Denier and Tex are measures of fiber and yarn linear density. Denier is the weight in grams of 9,000 meters of fiber yarn; Tex is the weight in grams of 1,000 meters.

Table 4 - 1

FIBER CHARACTERISTICS

Fibers	Moisture Absorption	Fatigue Resistance	Tensile Modulus	Tensile Strength
Nylon	Medium	High	Medium	High
Poly(ethylene terephthalate)	Low	High	High	High
Kevlar®	Medium	*	Very High	Very High
Polypropylene	Low	High	Low-Medium	Medium-High

* Depends on finish or coating.

followed by slow hot-drawing, be made into a rigid, high-modulus, high-tensile-strength fiber (Sheehan and Cole, 1964, Spruiell and White, 1975). Commercial synthetic fibers will vary in properties depending upon the engineering application.

4.2.1.2 State of the Art

Experiments to date (Goodyear Aerospace Corporation, 1973; Bell Aerospace Corporation, 1973; Aerojet Surface Effect Ships Division, 1974; Swallow, et al., 1971; Rohr Industries, Inc., 1976) emphasized the use of nylon and to a lesser extent polyester. There have been more limited studies on the aromatic polyamide, Kevlar® produced by DuPont. Nylon is the fiber currently used in commercial and military vehicles. The comparative experimental study by Goodyear Aerospace, 1974, in the Arctic SEV Program found nylon and polyester adequate. The results achieved in these studies do not seem to be independent of considerations of fiber denier or yarn construction. Avon Rubber researchers (Kelly et al., 1974) have noted the deterioration of tear and adhesion properties of nylon fabrics after service and attributed this to water absorption and fatigue.

4.2.1.3 Gaps in Knowledge

Experimental studies to date have been limited in scope. The relative capabilities of the different fibers to survive fatigue and similar tests during water immersion have not been adequately investigated. For example, no study of polypropylene exists despite the superior hydrophobic character of this material. Frequently polypropylene has been eliminated from consideration in similar applications because of its low softening temperature; it also appears to exhibit a bonding problem (Bell Aerospace Corporation, 1974). However, it is worthy of further consideration.

4.2.1.4 Conclusions

1. The extent of knowledge of performance of different base fibers seems limited.

2. It does not seem to be known how well nylons, polyesters, Kevlar®, and polyolefins retain their mechanical properties in the SEV environment. It might be expected that this environment would have the greatest influence on nylon because of the well-known effect of moisture in lowering the modulus and tenacity of nylons (Morton and Hearle, 1975; Starkweather, 1973). Some indication of the problems resulting from this is given by Kelly et al., 1974.

3. One should not consider the fibers alone, but rather the whole fiber-adhesive-rubber system.

4. More information is also needed on the influence of sea water on the entire system under dynamic conditions.

4.2.1.5 Recommendations

1. Further studies of the relative merits of candidate commercially available fibers, particularly polyester, Kevlar®, and polypropylene, should be undertaken.

2. Consideration might also be given to using yarns comprised of large diameter filaments (large dpf - denier per filament - yarn). This will decrease the wicking of water up from the finger edge.

4.2.2 Fabric Construction

4.2.2.1 Principles

The mechanical properties of woven fabric are a function of the yarn and fabric construction (see Figure 4-2), as well as the fiber properties. The less the yarn twist and yarn crimp, the more efficient the translation of fiber strength into fabric strength. Yarn crimp in woven fabrics is minimized by using low yarn twist and long float weaves, e.g., basket weaves. Additionally, the lower the yarn twist and the more open the fabric (the lower the pick and end count for a given yarn construction and weave pattern), the greater the freedom of relative yarn and fiber motion during fabric deformation. This enhances the fabric resistance to tearing and flexural fatigue, and decreases the fabric stiffness.

These considerations determine the properties of coated fabrics as well. However, the magnitude of their effects is significantly less, depending upon the coating thickness, adhesion, modulus, and level of penetration into the fabric structure. A flexible coated fabric is generally achieved with low denier yarn twisted less than a turn per inch and woven into a low count, open, long-float basket weave. Large yarns, highly twisted and plied, and woven into high count, plain weave constructions generally produce thick, stiff, coated fabrics.

Fabric construction also determines, in part, elastomer adhesion. A yarn spun from chopped fiber is bulkier than continuous filament yarn, thereby permitting greater mechanical adhesion of the elastomer. A blend of two different fibers, e.g., cotton and nylon, also can be used to improve elastomer adhesion. A fabric tightly woven from high twist yarns usually exhibits lower coating adhesion

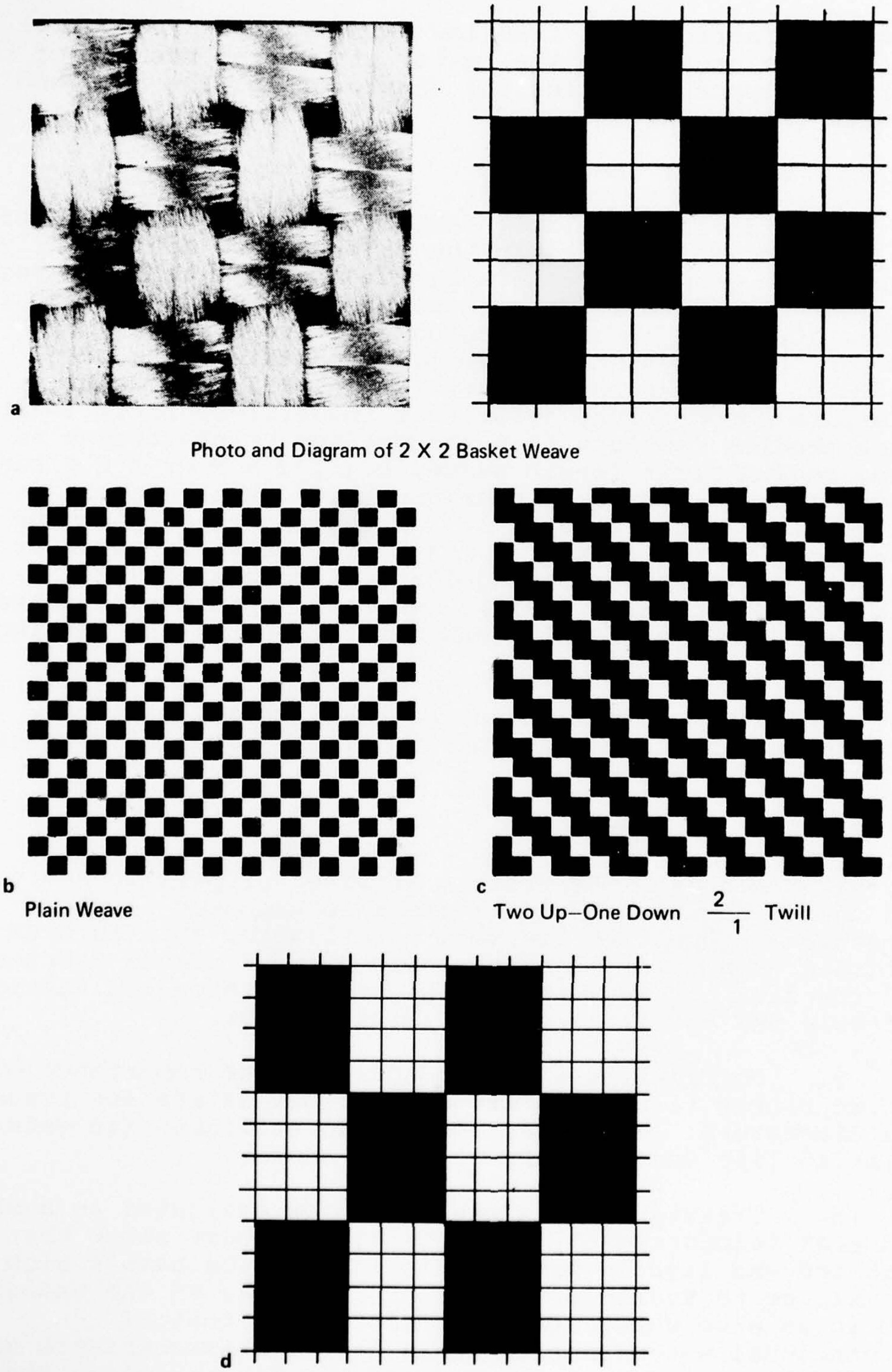

FIGURE 4-2 Weave patterns.

than open fabric woven from low twist yarns. Mechanical adhesion is greater in the latter structures because of the increased opportunity for the elastomer to flow into and between the yarns.

4.2.2.2 State of the Art

Commercially available fabrics were used for most of the SEV studies reported in the literature. Additionally, most of the data reported is based only on laboratory tests. Consequently, definitive conclusions on the effects of fabric structure on skirt performance are not possible. However, three systematic laboratory studies have been conducted (Bell Aerospace Corporation, 1973; Goodyear Aerospace Corporation, 1973; Rohr Industries, Inc., 1976). These studies conclude that the optimum reinforcement is an open, medium float length weave, e.g., 2 x 2 or 3 x 4 basket weave, fabric woven from moderate twist yarn. Recent limited laboratory studies at Bell Aerospace Corporation have shown that a closed, 3 x 4 basket weave is superior to an open basket weave in flagellation resistance (Bell Aerospace Corporation, 1977). However, open basket weaves exhibited superior tensile and tear strengths and coating adhesion.

Detailed information on the adhesive and elastomer penetration are not given for any of the materials evaluated in any of the studies.

4.2.2.3 Gaps in Knowledge

1. Although the effects of fiber properties and yarn and fabric construction parameters on uncoated fabric mechanical properties are well established, this is true to a lesser extent for light-to-medium weight coated fabrics, and few data are available on high-strength coated fabrics suitable for use in large SEV skirt systems.

2. Conflicting views on the relative importance of coated fabric flexural stiffness for SEV skirts are found in the literature. The effect of fabric stiffness (in water) on skirt life does not appear to be known.

3. Triaxial fabric has yet to be evaluated as a skirt and seal reinforcement. Studies to date have shown that uncoated and lightly coated triaxial fabrics have a high resistance to tearing. The shear stiffness of the uncoated fabric is also substantially greater than that of conventional woven fabric. This latter characteristic may significantly increase the life of the fingers along the sides of ACV's. The locked nature of triaxial fabric may also reduce edge fraying.

4. Automobile tires have used multiple plies of unidirectional fabrics as a reinforcement for decades. A potential shortcoming of this approach for SEV skirts might be low tearing strength. Once a tear is initiated it will propagate between the plies, causing delamination. The use of multiple plies of fabric will also raise the composite bending stiffness. However, the possible merits of this type of structure should be evaluated.

5. The advantages of eliminating seams by utilizing contour-woven fabric have not been evaluated.

4.2.2.4 Conclusions

1. The effects of fabric construction parameters on skirt performance have yet to be fully established. It is anticipated that the optimum material will vary with vehicle size and design, vehicle mission, and skirt design.

2. Most of the studies to date indicate that the optimum skirt reinforcement is an open, medium float length (e.g., 2 x 2 or 3 x 4 basket weave) fabric woven from moderate twist yarn. However, this conclusion is based on laboratory testing and has yet to be verified by statistically designed service testing.

4.2.2.5 Recommendations

1. The most important consideration with regard to the fabric reinforcement is the design methodology. It should be remembered that the fiber is the material and the fabric is an engineered structure. Fabrics should be designed and woven to meet the specific requirements of SEV skirt systems, which unfortunately are not well defined.

2. An extensive, systematic study of the effects of fabric structure on skirt performance should be conducted. These investigations should include both laboratory testing and field trials. The study would increase our basic understanding of the mechanical response of high strength, heavy coated fabrics and determine the effects of water immersion on fabric properties and the relative importance of fabric stiffness.

3. The relative merits of triaxial fabric should be investigated. The locked, truss-like geometry of this structure might make a superior skirt reinforcement. Unidirectional fabrics, like those used in tires, and contour-woven fabrics should also be evaluated.

4.3 Coatings

4.3.1 Available Materials

A wide range of elastomers are commercially available including natural rubber, polybutadienes, butadiene-styrene copolymers, butadiene-acrylonitrile copolymers, polyisoprenes, polychloroprenes, isobutylene-isoprene copolymers (butyl rubber), ethylene-propylene copolymers (EPM) and terpolymers (EPDM) among others. As elastomers are never used in the pure, raw state, but rather are mixed with fillers such as carbon black and oil, blended with other polymers and vulcanized, the range of possible rubber compounds that could be used for coatings is vast.

Properties such as abrasion resistance and wear (Kienle et al., 1971), friction (White and Lin, 1973) are largely determined by elastomer type. Generally, mechanical properties of different elastomers tend to be roughly similar at the same value of $(T - T_g)$, where T_g is the glass transition temperature. Adequate low temperature behavior and low hysteresis necessitates using an elastomer possessing a low T_g. Styrene and acrylonitrile copolymers of polybutadiene have higher T_g's.

Solvent resistance is related to the chemical nature of the structural unit. Thus hydrocarbon elastomers absorb petroleum oils but are hydrophobic. Acrylonitrile-butadiene copolymers and polychloroprene contain polar groups and are oil resistant.

With the exception of EPM, the elastomers cited above are unsaturated vulcanizable materials which can be crosslinked with sulfur. Other elastomeric materials which do not require vulcanization exist, namely, the block copolymers, which include the butadiene-styrene type (e.g., Shell Kraton, Phillips Petroleum Solprene), polyester types (e.g., DuPont Hytrel) and polyolefins (e.g., Uniroyal TPR). These materials consist of rigid segments with flexible chains connecting them, and behave as vulcanizates. Thus Shell Kraton has a (polystyrene)-(polybutadiene)-(polystyrene) structure, and below processing temperatures, polystyrene agglomerates and forms rigid glassy regions which act as crosslinks. They may be compounded in a manner similar to conventional elastomers; for at elevated temperatures, they soften and melt. The Shell and Phillips Petroleum material cannot withstand more than about 80 °C. The ability of these materials to withstand the dynamic conditions of skirts without creep, and of some to withstand radiant heating from the sun without softening, makes their application questionable.

4.3.2 Compounding

As mentioned in the previous section, the elastomers' used are compounded with reinforcing agents such as carbon black (Payne and Whittaker, 1971) to achieve desired vulcanizate mechanical properties. In addition other additives are included to improve processing, to provide protection against oxygen or ozone damage, to improve flex life, to enhance adhesion to substrates including fabrics, and to act as curatives. In the latter category would be sulfur and accelerators. The range of possible compounds is thus almost limitless. Each rubber fabricator has compound recipes to serve for particular applications, such as the tread, sidewall and carcass of a tire - with each type of tire (automobile, truck, aircraft) having appropriately different recipes. Rubber may be blended and compounded to obtain desired combinations of mechanical properties such as dynamic characteristics (Payne and Whittaker, 1971) and abrasion resistance (Boonstra, 1973).

Generally the addition of carbon black increases modulus, tensile strength, hysteresis, electrical conductivity, tear resistance, and abrasion resistance of rubber compounds. Decreasing particle size of the carbon black and increasing surface area per unit volume at constant loading further increases these properties. Another variable of importance is the degree of agglomeration of the particles which is referred to as "structure". Generally, increasing structure has an influence similar to that of decreasing particle size. Medalia, 1970, and Kraus, 1971, have developed general approaches to correlation of mechanical properties with carbon black loading in terms of an "occluded volume" which combines loading, particle size and structure.

The addition of mineral oil tends to "extend" rubber by adding a low molecular weight component. It is possible to process higher molecular weight polymers by oil extension and also to incorporate higher levels of reinforcing fillers.

4.3.3 Vulcanization

After being fabricated into desired shapes the rubber compounds are raised to elevated temperatures for extended periods in order to crosslink them. Without the vulcanization process, the mechanical properties are not suitable for most applications. However, the level of curatives and the temperature and extent of the vulcanization process can greatly modify the crosslink density and mechanical properties such as modulus, tensile strength and elongation to break. Generally, curative level, accelerator content and vulcanization conditions need to be optimized for each product (Stephens, 1973).

4.3.4 State of the Art

Early studies on coatings used arbitrarily selected materials which appeared to give desired flexibility characteristics in skirts. Attempts at extensive comparisons of materials for coatings were reported by Goodyear Aerospace Corporation, 1973, and Bell Aerospace Corporation, 1973. The materials investigated included natural rubber/polybutadiene blends, neoprene, ethylene-propylene terpolymer, nitrile blends, and poly(vinyl chloride) (PVC). Much of the early work in this area used the PVC/nitrile system, which is unsuitable for low temperature applications. In general, blends of natural rubber (NR) with cis-1,4-polybutadiene (BR) reinforced with the proper carbon black (CB) gave the best overall performance. Goodyear recommended the ratio of 65/35/40 for NR/BR/CB. Rohr Industries Inc.,1976, stated that NR/BR compounds possess outstanding resistance to flex cracking, flex crack growth, and abrasion and are low in cost and exhibit excellent low temperature properties. Deficient properties include ozone resistance and fuel resistance. The reports were vague on vulcanization systems and conditions.

4.3.5 Conclusions

1. Certain types of potentially promising elastomers with which there is extensive technological experience have yet to be evaluated as skirt/seal materials. Notably among these are butadiene-styrene random copolymers and their blends with polybutadiene.

2. Information on elastomers, curatives, compounding, processing and vulcanization conditions for coated fabrics is generally considered proprietary.

3. Nothing is known of the response of block copolymer compounds in such applications.

4.3.6. Recommendations

1. Evaluation of butadiene-styrene copolymers and their blends, and more extensive evaluations of compound variables and curing conditions are recommended.

2. Studies of the use of block copolymers for this application should be undertaken.

3. A firmer basis is needed for compound recipe optimization. Recipe contents and fabrication conditions should be reported.

4. Fire is always a potential hazard on and around military vehicles. Consequently, the effects of fire retardant additives on the properties of the elastomer should be considered.

4.3.7 Low Friction Coatings

Very little effort has been expended to protect the elastomer surface of the finger against abrasion. The elastomer itself is abrasion resistant to some extent but is subject to degradation from environmental elements. It also exhibits a high friction coefficient under sliding conditions (Ksieski, 1973). The addition of a low friction and abrasion resistant coating to the surface can protect the elastomer against environmental elements and abrasion, and reduce the friction coefficient between the elastomer fingers under sliding contact.

4.3.7.1 Coating Materials

Several materials are commercially available which will reduce the friction coefficient. Some are self-lubricating and will protect the rubber surface against abrasion. They are:

(a) Polyurethanes

As a hull coating polyurethanes are being used as wear resistant and low friction materials against ice (U.S. Coast Guard, 1976). They are presently used as a coating material in situations in which abrasion is a problem and have brought about significant increase in life. Some are filled with ceramic, metal, or PTFE (see (b) below) to enhance their frictional properties and increase wear resistance. Of particular interest are the nonsolvented polyurethanes which exhibit four times the bond strength of the normal solvented system. All of the above materials are elastomeric as a coating material and can be applied at very thin dry film thicknesses (~0.002") or very heavy dry film thicknesses (~0.050").

(b) Polytetrafluoroethylene (PTFE)

The PTFE coated rubber is a layer of PTFE powder dispensed on a tacky surface of adhesive coated rubber. After the adhesive cures, the loose powder is removed, leaving a top coat of PTFE on the rubber backing.

(c) Fluorinated Elastomers

The fluorinated rubber is made in a commercial process in which the surface of the rubber is reacted to produce a Teflon-like surface. The process is considered to be promising for pump seal applications in reducing the friction of rubber sliding against various materials.

(d) Monomers and Copolymers

There are commercially available monomers and co-polymers which when sprayed on the surface from a water suspension adhere to the substrate and produce a surface finish similar to polyethylene or other polyolefins. They show a significant reduction in friction coefficient when sliding against many materials.

(e) Monomolecular Film

The dimethyl amides are applied from a water suspension, by spraying, brushing, or dipping. They form a very thin (monomolecular) film on the surface of the substrates and exhibit low friction by lubricating the surface. They can be removed by scraping the surface but display self-healing characteristics in which the adjacent molecules move to recoat the damaged surface. In this application the lubricant has to be applied periodically by spraying a water slurry.

(f) Dry Film Lubricants

Resin-bonded MoS_2 and graphite are solid lubricants which are commercially available and are applied by spraying. There are several commercially available variations on the market which utilize vinyls, epoxies, or phenolics as binders for adhesion to the substrate.

Some of the above lubricants may not be acceptable for the application due to impact loading, bond fatigue or inability to apply the lubricant coating thick enough to withstand sustained sliding. Several advantages make urethane coatings the most probable candidates for success. They are:

- ability to be applied at variable thicknesses
- good bond strength
- ability to be filled with additional wear resistant materials
- ease of application

- range of color selection

- variable flexibility.

With the exception of color selection the above advantages are obvious. The selection of color is important because the coating can be applied in various layers of different colors. All materials wear at some rate. As the topcoat begins to wear, the color from the next layer becomes evident and immediate repairs can be made before catastrophic failure occurs. Most of the materials can be applied in the field by spray or brush and therefore, immediate repair is possible.

4.3.7.2 Conclusions and Recommendations

1. Low-friction coatings have not been utilized despite the promise of affording protection of the elastomer top-coating.

2. The above suggested coatings should be screened by applying them to an elastomer surface and measuring the friction coefficient and wear resistance against various materials under variable conditions. A test rig which could be used to evaluate the frictional properties of the coatings is shown in Chapter 7 of this report. Those materials which show merit can be applied to vehicle fingers for full-scale tests.

4.4 Adhesives

4.4.1 Background

Even for the simplest of systems adhesive failure is a complex and incompletely understood phenomenon. For example, researchers are not in agreement as to the fundamental molecular mechanisms responsible for one substance adhering to another. There may in fact be several mechanisms involved. While it is normally assumed that Van der Waals type forces are largely responsible for the bonding of most adhesives, there is evidence that stronger primary bonds such as covalent bonding are active in some systems. Alternatively, the term adhesion is used to describe connections that owe their strength largely to mechanical interlocking across a surface.

The calculations of stress (and strain) across an interface is a difficult problem. There are often large differences in modulus between adhesives and the adherends. This can give rise to complex stress states even for comparatively simple bonding, e.g. substantial shear stresses may be induced in a thin layer of adhesive under tension between fairly rigid plates. The problem is further complicated in that many adhesives are viscoelastic and exhibit strong loading rate and temperature dependence. Furthermore almost all adhesive joints have ends or small regions of debond (dewetting) where the stresses are mathematically singular.

Failure of fabric (or fiber) reinforced rubber is a complex phenomenon that is often associated with delamination or debonding where ultimate failure of the composite is located in the region of the adhesive bond. It is important to note that a reinforced rubber article (skirt, seal, tire, hose, etc.) is always a multicomponent system possibly including fillers, plasticizers, bonding agents, antioxidants, curing chemicals, etc. and not just a combination of the two components, elastomer and fabric. Albrecht, 1973, recently described some of the factors influencing adhesion between rubber and cord.

The existing technology regarding fabric reinforcement of elastomers dates back to the early 1900's when cotton fabric was used with no adhesive treatment for tires. As automotive demands became more sophisticated, rayon filament was introduced to replace cotton. The limitation of the early rayon reinforcement was, in fact, confined to poor adhesion. Initially, reclaimed rubber-casein-latex adhesives were used to improve this defect but this particular adhesive formulation did not truly satisfy the industry requirements (Garner and Williams, 1950). Attention was subsequently directed toward adhesives based upon latex and thermosetting resins, specifically, resorcinol-formaldehyde-latex adhesives (commonly called RFL adhesives) were developed (Thoman and Gilman, 1949). In the late 1940's nylon-66 was introduced as a tire reinforcing material and the RFL adhesives are also suitable for bonding nylon fabric to the various elastomers.

Two fundamentally different bonding processes are in common usage. The first, a dipping process, uses resorcinol-formaldehyde resins and latex (RFL) (DuPont de Nemours, 1938). Adhesion depends on both the composition of the dip and drying conditions (Albrecht, 1973). More recently, direct bonding processes have been developed in which resorcinol formaldehyde-donor and active silica filler are added to the rubber compound (Shchicko, 1966; Kamensici, 1966). This mixture called a "direct bonding compound"--(this particular direct bonding process is called the Cohedur Process (RFS))--adheres well to undyed fabrics or steel cord after curing. Albrecht, 1973, reports that it is necessary to have all three components present since they affect each other synergistically. The effect with carbon black for example is much less than with the silica filler.

Polyester fibers and glass fibers have been used recently in the tire industry. Moreover, natural rubber has been gradually replaced over the years by synthetic rubber and more recently new materials including cis-polybutadiene and ethylene-propylene rubber (EPM) have been introduced into the rubber industry. These newer elastomer formulations require variations on adhesive formulations.

In summary, the existing technology relating to the requisite adhesion of fabric reinforced elastomers for tire applications forms the basis of the emerging technology of coated fabrics applied to the development of materials for skirts for surface effect vessels.

The limitations inherent in using the RFL adhesives for bonding polyesters to rubbers have largely been overcome by a variety of formulation variations. In addition, several new classes of adhesives have been used successfully for bonding polyesters to elastomeric coatings. These include isocyanates, blocked isocyanates (Meyrick and Watts, 1966); ethylene ureas (Teijin, 1963); modified poly(vinyl chloride) (Little, 1961); polyepoxides (Craig, 1969), and a new single-dip system based upon triallylcyanurate modification of conventional RFL systems (Aitken, et al., 1965).

It is important to realize that all the components of an elastomer recipe can have a significant effect on adhesion. All these effects cannot be reviewed here but a few brief examples may serve to emphasize this important fact. Albrecht, 1973, gave a comprehensive review of the influence of rubber composition, dip, type of curing process, etc. on adhesion between rubber and textile (or steel) cord. Included are discussions of the influence of: 1) the formulations of RFL dips, 2) the sulfur dosage, 3) the type of cord, 4) the presence and type of accelerators or retarders, 5) the Mooney scorch time, 7) the presence and/or type of antioxidants, 8) the type of rubber, and 9) any other rubber compounding agent.

Erickson, 1974, discussed the dependence of tire cord adhesion on elastomer properties. Among other facts he reports that: 1) Gent, 1971, confirmed a viscoelastic dependence of peel strength that can be treated by the WLF equation* (Williams et al., 1955), 2) higher values of

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* An equation based on the principle of time-temperature correspondence which reduces the data by means of a shift factor to a reference temperature, commonly the T_g.

adhesion occurred with those elastomers that exhibited high elongation and high strength, 3) elastomers which were slow curing tended to have increased adhesion, and 4) elastomers with high Mooney viscosities tended to have higher adhesion to cord.

The recent study by Lehmicke, 1974, on "Effects of Moisture in Composites Skim Stock and Polyester Tire Cord" seems particularly pertinent to skirts and seals. For the stocks studied, cord strength, adhesion, fatigue life, and resistance to cure blister are all adversely affected by higher-than-normal water content. While this study was primarily directed toward the presence of water in the green stock before cure, some of the conclusions are also applicable to the presence of water in the post cured rubber. It is reported that blistering can be prevented by cooling at the end of cure before releasing pressure. All the deleterious effects can be reduced by improving the tire cord dips and by reducing or eliminating the amine generating components in the cure system. Elastomers containing polybutadiene and SBR perform better than those containing natural rubber. High water vapor transmission rate contributes to good fatigue life, and low moisture regain contributes to good blister resistance while adhesion of the different elastomers does not correlate with either of these. These researchers attribute this lack of correlation to the inordinate moisture absorption of the RFL dip which may override the influence of the skim stock properties.

4.4.2 Gaps in Knowledge

Apparently there is no unique technology related to the application of coated elastomeric fabrics for skirt materials, per se. The state-of-the-art regarding coated fabric adhesives for this unusual application is essentially confined to the application of existing products developed for the large-volume tire industry. The relatively small market associated with skirt materials is insufficient to influence adhesives development.

The fundamental limitations of the technology of tire cord bonding are, of course, carried over to the more specific application considered here. There is no well accepted fundamental explanation which can be used to guide completely new adhesive formulation. The existing adhesive which works rather well for a wide variety of elastomer and fabric systems, namely the RFL-based adhesive, has been in use for many years and, presumably, a significant breakthrough with respect to adhesives for skirts will follow the development of improved adhesives for the much larger tire market.

4.4.3 Conclusions

1. Nylon and rayon are more easily bonded than polyester to a wide variety of elastomer coatings.

2. Resorcinol-formaldehyde-latex adhesives are typically used for bonding nylon and rayon to any of the variety of synthetic rubbers as well as historically used natural rubber.

3. Adhesives presently used are virtually all proprietary.

4. Developments of new adhesives, and variations of existing adhesive formulations will follow developments in the adhesion of tire cord to the elastomeric component of automobile tires.

5. Actual performance of coated fabrics may not vary monotonically with adhesive strength since, at high levels of adhesion, tear strengh of the resulting composite may be sacrificed. (See Section 5.1)

4.4.4 Recommendations

1. Although an explicit relationship between structure and properties of the adhesive formulations has not been widely accepted, many of the well accepted physico-chemical principles regarding functional group interactions, solubility parameters, chemical reactivity, and miscibility of chemically similar components can be employed to describe the overall effects observed with respect to the efficacy of adhering synthetic fabrics to elastomeric coatings.

2. Detailed specifications of the formulations should be provided to permit development of rational correlations between molecular structure of the adhesive formulation and the observed coating performance.

3. Since skirt requirements are quite specific evaluations should involve salt-spray testing, cold crack performance testing, organic solvent resistance, and presumably, the large variety of tests which are imposed upon surface coatings used for marine applications.

4.5 New Materials Concepts

It is recognized that the R & D efforts to date have been essentially restricted to off-the-shelf materials, and that elastomer-coated fabrics have appeared to be the best candidates. However, if one views the problems inherent in such materials when subjected to the strenuous service conditions involved in ACV or SES operations, the question arises: Is there a better concept?

Analysis of all the data available suggests that, as is often the case with composite structures, failure involves the fiber-polymer interface. While interfaces are inevitable when one wishes to obtain the benefits of composite principles, interfaces are a source of stress concentrations, and especially so when the materials joined have very different moduli. Hence, in principle, one may well consider either improving the nature of the interface (or "interphase") or removing the interface altogether. In other words, since there appear to be severe limits on what can be achieved with a coated fabric, attention should be given, even in a speculative way, to other possible concepts for a skirt/seal material.

Possible alternate materials sytems that could eliminate or at least minimize potentially troublesome interfaces include the following:

1. A monolithic sheet of a tough, abrasion-resistant polymer. This approach would eliminate the adhesively bonded interface in the present systems, and could open up new design possibilities. Skirt fingers might then be molded, thus eliminating seams and permitting the fabrication of complex (e.g., double-curved) skirt designs. Attachments of reinforcements might also be molded in. Materials such as polyurethanes or moldable polyesters could by considered for this purpose.

2. Oriented polymers. Many such materials have been available, both uniaxially and biaxially oriented, such as polypropylene and polyesters (though existing types may not be suitable "as-is"). The new concept of molecular composites, in which highly oriented molecules perhaps in crystallites are embeded in a matrix of the same type (Society of Plastics Engineers, 1975), may well be of potential interest.

3. A flexible metallic matrix which is filled with a dry lubricant such as Teflon or MoS_2. The material can be made by cosintering any metal which is available in powder form with the lubricant. The density and pore size can be controlled to produce a given strength and lubricant content. The materials's appearance is similar to that of a laminated rubber fabric.

4. A chopped- or mat-fiber-reinforced composite. The material could be a fiber/elastomer composite manufactured by vacuum-bag molding. The fiber could be graphite, boron, glass, polyamide, or a combination hybrid. In addition, dry lubricants (MoS_2 or graphite) could be added to the

composite to produce low-friction and low-wear characteristics.

5. Stiff articulated members, attached to the bag structure, which can flex easily on contact with obstacles (ground or waves).

One may raise objections to any particular one of these proposed systems,e.g., insufficient strength or unavailability on a large scale. However, creative thinking is inherently possible here, and should be encouraged. The true innovators among the suppliers, and among polymer scientists in general, should be consulted.

CHAPTER 5

FABRIC REINFORCED COMPOSITE

5.1 Interaction of Composite Components

As discussed in Section 4.1, present skirts are a composite comprised of three components: 1) woven bundles of polymeric filaments; 2) a thin adhesive layer between the filaments and the elastomer; 3) an elastomer coating. The composite's performance not only depends on the properties of each of the components but also on each component carrying out its function in the structure. The components must be carefully selected, and their properties and processing procedures must be compatible. When a composite is carefully designed and the manufacturing processes optimized, it exhibits certain properties that can not be achieved with any of the components by themselves.

The major function of the filaments in a fiber reinforced composite is to provide strength. In particular, significant restraint must be provided by the reinforcement of a skirt material to maintain coating strains at an acceptable level. (Goodyear Aerospace Corporation, 1972). Without proper reinforcement, the coating will be subjected to large cyclic strains and undergo rapid fatigue degradation.

An important component in a composite is the adhesive layer at the interface between the reinforcing filaments and the elastomer coating. The adhesive must have both the proper chemical characteristics to bond to the two components, and the proper mechanical properties to withstand the high stresses that can occur at the interface due to the large difference in moduli between the rubber and the filaments. A poorly bonded area at the interface can cause failure of the bond during fabric stressing. The resulting discontinuity will be a possible site for initiation of coating delamination and will act as a point of stress concentration for delamination propagation. It will also decrease the composite rigidity.

A void or an air pocket at the interface will also cause a stress concentration. Additionally, the resulting unsupported length of filament will be subjected to buckling when compressive stresses are imposed on the filaments during skirt flutter and flagellation. This may lead to early fatigue failure.

The adhesive layer must maintain a good bond between the filaments and the elastomer after immersion in sea water. To prevent wicking between the filaments, the adhesive layer should thoroughly penetrate the yarn. However, this usually increases the coated fabric bending stiffness and decreases its fatigue life and tear strength.

The bending stiffness of woven fabric reinforced composites is increased by increasing the filament and rubber moduli, filament diameter, yarn size, yarn twist, yarns per unit width, weave tightness, and adhesive penetration into the yarn cross section, and decreasing weave float length. Application of a thicker layer of coating to the outer face of the fabric will also increase the composite's resistance to outward deformation while providing increased protection against abrasion. Resistance to inward deformation is assisted by the positive air pressure inside the skirt structure.

The use of multiple fabric plies is another approach to achieving greater composite tensile strength and stiffness. However, this design approach places very stringent demands on the strength of the bond between the plies. Multi-ply constructions investigated to date have exhibited poor performance due to cohesive failure (Bell Aerospace Corporation, 1973). However, they have been used successfully for many years in automobile tires, a similar structure exposed to somewhat similar pressure loading conditions.

5.2 Methods of Manufacture

The basic operations in the manufacture of material for SEV skirts are listed in Figure 5-1. They include twisting and plying yarn, weaving yarn into fabric, stabilizing the fabric, applying a primer and/or tie coat, applying and curing an elastomer. The properties and performance of the final product depend on the processing methods, particularly the manner in which the elastomer is applied.

Reports on skirt development programs note the construction of the fabrics investigated and give a brief description of the process used to coat them. However, none give detailed information on process parameters, such as times, temperatures, pressures, coating machine details. The effects of process parameters on material properties also do not appear to have been investigated. Product uniformity is not reported.

The process parameters that must be considered in skirt manufacture are given in Figure 5-2. The possible effects of the various processing methods and process parameters on material properties and uniformity are discussed below. The relative merits of alternative processes for skirt and seal fabrication are considered.

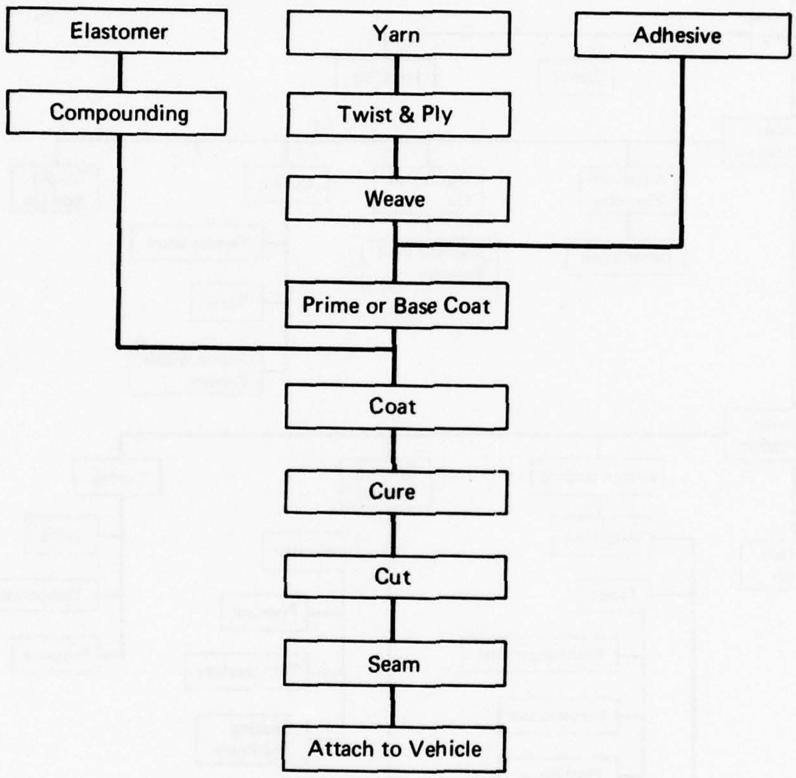

FIGURE 5-1 Skirt and seal manufacture.

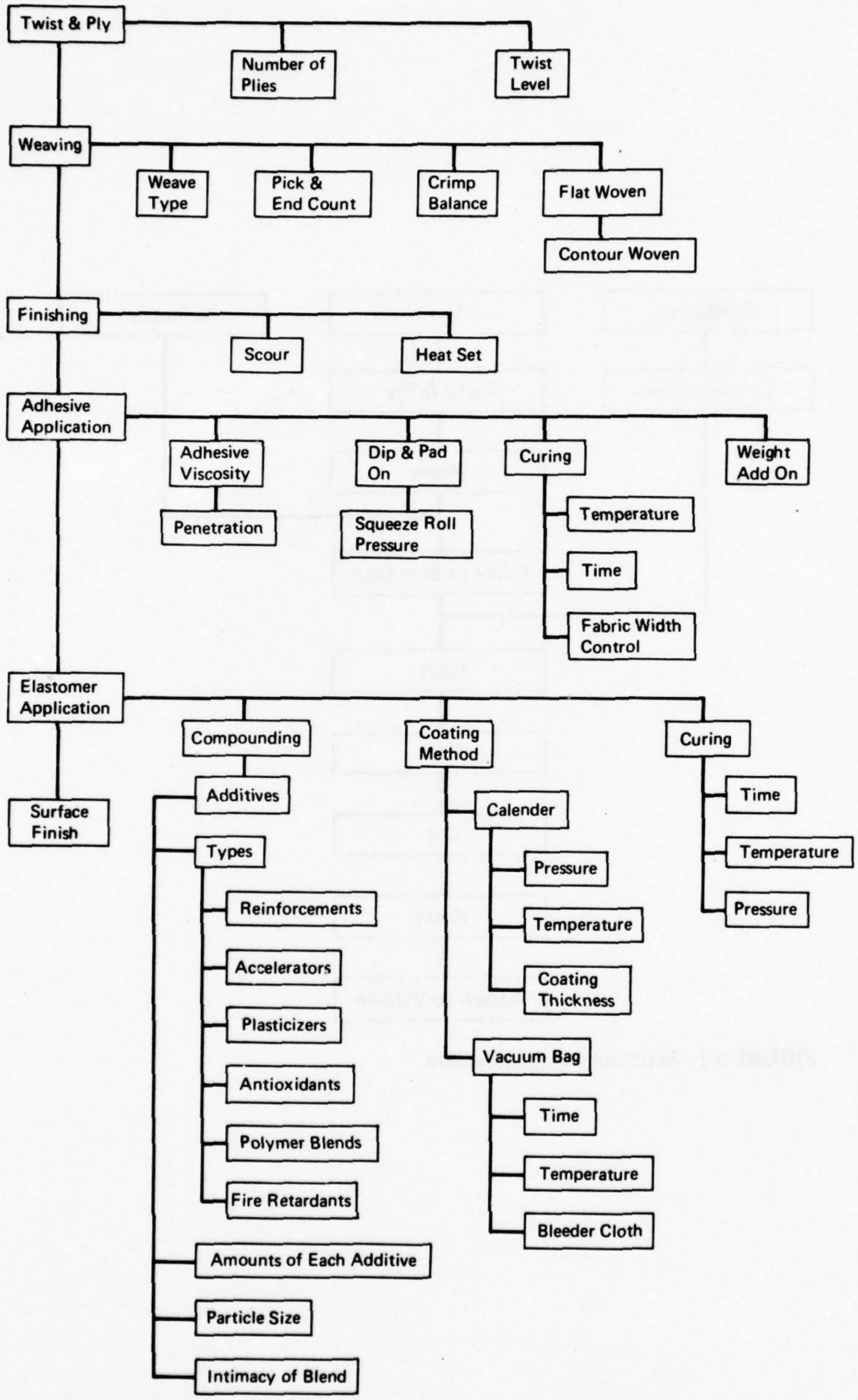

FIGURE 5-2 Process parameters.

5.2.1 Weaving

The yarn used in SEV fabric reinforcement is twisted on conventional textile twisters and then woven into fabric on conventional looms. The various process parameters and their effects on fabric properties are discussed in Section 4.2.2.

To minimize the number of seams in fabric seal systems for large SEV's, the widest possible fabric reinforcement should be used. Most fabrics used to date have been obtained from conventional manufacturers of industrial fabrics. Their equipment is usually limited to a maximum fabric width of approximately 80 inches. British Hovercraft Corp. is currently investigating the potential of wider fabric (British Hovercraft Corporation, 1976). However, organizations that produce Fourdriniers (the belt upon which paper is formed) have looms capable of weaving (single layer) very heavy fabrics with precise control of filling spacing in widths to 70 feet.

Machines currently available for calendering rubber to fabric are limited to a maximum width of about 83 inches. Consequently, the use of fabrics with widths greater than 83 inches restricts the method of applying the elastomer to hand lay up, pressure vacuum bagging, and autoclave curing. Laboratory test data indicate that this method of applying the elastomer is comparable to calendering (Rohr Industries, Inc., 1975).

Looms currently available can weave triaxial fabric* (See Section 4.2) with yarns to 1,500 denier, giving, with nylon, fabric strengths of 800 lbs/inch width. Minor modifications to the looms would permit weaving fabric with strengths to 1000 lbs/inch. Heavier fabrics would require designing a new loom.

Unidirectional tire cord type fabrics with small filling yarns about an inch apart can be readily produced in wide widths and with very high numbers of large denier warp yarns per unit width. The success of this type of material as a tire reinforcement suggests its consideration as a reinforcement for SEV skirts.

Methods are familiar to the textile industry for coating sheets of yarn and winding them on a beam and also for separating the coated ends and winding each one on a

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* N. F. Doweave, Inc., Valley Forge, PA

separate package. Consequently, an adhesive tie coat could be applied to yarn prior to weaving. This would permit increased adhesive penetration into the yarn and thereby enhance the rubber-to-filament bond, possibly increasing the resistance of the coated fabric to delamination during repeated flexing in a water environment.

As noted in Section 4.2, yarn can be woven into three dimensional surfaces by a process called contour weaving. Doubly curved surfaces are produced by controlling warp yarn let-off and dropping out warp yarns during the weaving. Only one company in the United States has expertise in contour weaving.* Large fabric surfaces with strengths to 1500 lbs/inch width can be produced on current equipment.

In order to contour weave a dimensionally stable fabric, heat set yarn must be used. The ends of the warp yarns dropped to achieve a tapered shape might be potential sites for failure initiation. Additionally, the application of the rubber coating to the fabric would require special tooling and be limited to hand lay-up, vacuum bagging techniques.

5.2.2 Application of Adhesive

Chemical adhesion is necessary to achieve a strong bond between the elastomer and synthetic filament yarn fabric. Primers provide this adhesion by reacting simultaneously with the fabric and the rubber during the vulcanization process. However, before the primer is applied, the greige fabric should be scoured to remove any spin finish and warp size. Failure to remove these processing aids will hinder adhesion of the elastomer to the fabric.

After scouring, the fabric is usually heat set. This renders the fabric more dimensionally stable.

Primer may be applied by dipping the fabric in the solution and then passing the fabric between a pair of squeeze rolls to force the primer into the fabric structure and to remove excess primer. The openness of the yarn and fabric structure, coating viscosity, and squeeze roll pressure all affect the adhesive penetration into the fabric and the weight add-on. Thorough penetration of the adhesive into the fiber bundles will improve the fabric wick resistance and the strength of the bond between the elastomer top coat and the fabric. However, it also

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* Woven Structures Division of HITCO, Compton, Calif.

increases the fabric rigidity. If fabric flexibility is the major performance consideration, thorough penetration of the primer into the fiber bundles is not desirable.

For maximum flexibility, a primer such as a blocked isocyanate may be added to a base coat and applied to the surface of the scoured fabric by the several methods discussed in Section 5.2.3 (predetermined amount of coating methods).

A base coat and a tie coat may also be applied to the fabric after application of the primer or in lieu of a primer, and prior to applying the elastomer top coat. Base coating is generally applied from solution. It affords "processing tack" or temporary, in process adhesion.

A tie coating may be applied in the same manner as the base coat, except that the rubber formulation in solution is adjusted to increase its affinity to the top coat or base coat as deemed necessary.

No information appears in the literature on the processes used to apply primers to the coated fabrics used to date for SEV skirts, or even if primers were used.

5.2.3 Application of Elastomer

As discussed in Section 4.3, elastomer formulation or compounding is very important. A balance between physical property requirements, bondability, and processability must be achieved. Fillers must be added to the elastomer to achieve certain physical and chemical properties. However, care must be taken not to extend or dilute the polymer too much, or the strength of the bond between the elastomer and the fabric may be decreased.

Once compounded, the elastomer must be designed to flow readily to form a uniformly smooth film and to flow into the interstices of the fabric. It also must wet the fabric.

There are two basic methods of coating - solution coating and solids coating. A fabric may be coated by one or the other method, or a combination of the two. Solution coating generally utilizes either a horizontal or vertical drying or curing oven behind or over the coating head. The coating heads are designed to coat one side at a time or both sides simultaneously. The three basic solution coating procedures and the various processes used are enumerated below:

1. Apply an excess, wipe off surplus and leave desired coating thickness.
   - a. Knife and blade coaters
   - b. Bar or rod coaters
   - c. Air knife coaters
   - d. Squeeze roll coaters
2. Apply predetermined amount of coating.
   - a. Reverse roll coaters
   - b. Cast coaters
   - c. Transfer roll coaters
   - d. Spray coaters
   - e. Extrusion coaters
3. Saturate in bath and remove excess
   - a. Dip and squeeze coaters
   - b. Dip and scrape coaters

Each approach has its own advantages and disadvantages.

In calender (solids) coating, a sheet of rubber is formed and applied to the fabric substrate. Compounds used for calendering must not shrink excessively, must not stick to the calender rolls, and must have sufficient tack or affinity for the substrate to which they are calendered. Because of high production rates (5-40 yards/min.) and the relatively high calender roll temperature required for a smooth film, considerable processing heat input to the stock is common. Therefore, the calendering compounds must have built-in processing safety or scorch resistance.

Generally the calender is used to apply coatings to one or both sides of fabrics at thicknesses from 3-4 mils up to 50 mils. Solution coating applicators are generally used to produce coating thicknesses less than four mils and to apply elastomers that cannot be practically applied with a calender.

In selecting the coating process most suitable for a specific product, it is necessary to know the physical and chemical properties of the fabric and coating to be used, and the end use performance requirements. These parameters are correlated with the fundamental characteristics of the various coating methods and the optimum method selected. A compromise is generally made since no one process or piece of equipment meets all of the requirements equally well.

Factors that must be known in order to select the optimum coating method include the following:

A. <u>Fabric to be coated</u>

1. Construction openness
2. Thickness
3. Dimensional stability
4. Heat and solvent sensitivity
5. Strength
6. Width and length

B. <u>Coating to be used</u>

1. Viscosity
2. Type of solvent
3. Rheological properties
4. Coating thickness to be applied
5. Surface desired
6. Penetration desired
7. Batch size

The elastomer applied to the fabric must be cured or vulcanized. This can be accomplished in a number of ways ranging from simple self aging, known as room temperature vulcanizing, to continuous hot air vulcanization processes. The process used will alter the surface characteristics and properties, e.g., flexibility, of the finished product. Some commonly used methods of vulcanizing elastomeric coated fabrics are festoon curing, drum curing, continuous press curing or roto curing, and hot air curing. Each method has advantages and disadvantages in terms of type of material it can handle, speed, cost, etc. The method used also affects the finished material properties.

Little information is available in the literature on the manner in which the fabrics used for SEV skirts have been coated. However, although process parameters are not given, it appears that in almost every case the elastomer was calendered.

The maximum width of material that can be processed with currently available calenders is about 80 inches. In an effort to decrease the number of seams in skirts for large SEV's, the feasibility of applying the rubber to the fabric by vacuum bag-autoclave curing has been evaluated. In this process a sheet of green rubber is laid on the fabric, a bleeder fabric laid on top of the rubber, and the assembly placed in an air tight bag. The bag is then evacuated, loosely rolled up, and placed in an autoclave to cure the rubber. The bleeder fabric permits gases given off during the curing to be withdrawn. Autoclaves to thirty feet long are available, thereby permitting the use of wide fabric.

Insufficient data is available at this time to predict the potential of this approach. Because of the lower pressure forcing the elastomer into the fabric structure, less penetration is anticipated than that achievable with a calender.

Surface finishes can impart important properties to the coated fabric. There are a variety of finishes which can be applied ranging from corn starch to talc and include the stearates and carbon black. The materials are absorbed into the coating during the curing process leaving a somewhat high-friction or slip finish depending on the finishing material. The particular "dust" finish used should vary with the end use of the coated fabric.

Other treatments can be applied to the surface of coated fabrics to give various effects. Vinyl, urethanes, and lacquers can be used to provide gloss surfaces or wear surfaces. The coefficient of friction of the surface can also be modified (See Section 4.3.7).

5.3 Gaps in Knowledge

Very little information is available in the literature on the manner in which the fabrics used for skirts have been coated. Consequently, it is difficult to judge the relative merits of the various types of processes or determine if the processes have been optimized. The extent of adhesive penetration into the yarns is not noted.

5.4 Conclusions

1. The effects of manufacturing process variables on material properties and uniformity have yet to be thoroughly evaluated.

2. The effects of fabric stiffness and adhesion on finger life have yet to be definitely determined. The effects of water immersion on coating adhesion and thereby fabric stiffness and finger life have also not been adequately evaluated.

5.5 Recommendations

1. Henceforth full documentation should be obtained for all skirt materials developed. This should include details on composition of all materials used to fabricate the skirts and the manufacturing process parameters.

2. A series of skirt fabrics with various levels of flexibility and elastomer adhesion should be made under known, closely controlled processing conditions. These fabrics should be extensively evaluated in the laboratory and in service on various types of SEV's of current interest, to determine the relative importance of elastomer-to-fabric bond strength in water and skirt stiffness. It is anticipated that the optimum fabric design may vary with skirt design and location on the vehicle, vehicle size and design, and vehicle mission.

3. Once the optimum fabric properties can be specified in terms of standard laboratory tests, the effects of manufacturing process parameters on these properties should be established. The best manufacturing process should then be optimized to insure reproducibility and product uniformity.

4. The relative merits of applying the adhesive tie-coat to the yarn prior to weaving in order to achieve more thorough penetration should be evaluated. Multiple plies of unidirectional fabric reinforcement also should be given further consideration.

5. To minimize the number of seams in seal systems for large SEV's, wide fabric woven on Fourdrinier looms, and contour woven skirts, should be evaluated.

CHAPTER 6

SKIRT SYSTEMS FABRICATION

Many different types of skirts or flexible seals have been fabricated for a wide range of vehicles. The design procedures, types of materials that have been utilized, the methods of fabrication, and the manner by which they have been reinforced and attached are discussed below.

6.1 Skirt/Seal Design Procedures

As discussed in Chapter 1, SEV skirts and seals must provide efficient cushion sealing with low drag, pitch and roll stability, acceptable ride characteristics, and slam load reduction. In order to perform these functions, the flexible coated fabric used, with attachments and joints, must exhibit adequate strength and life, minimum weight and minimum cost.

Present day skirt/seal design is based on a combination of analytical simulation modeling, small or reduced scale physical model test data, and the results of past and current experience derived from existing craft. Review of current skirt/seal programs indicates that there are four interrelated aspects involved in the design of surface effect vehicle skirt/seal systems:

a. Geometry and size of the skirt/seal system

b. Materials

c. Construction methods for skirt/seal systems

d. Maintenance limitations and/or requirements.

For additional discussion of loads and materials, see Chapters 3 and 4.

6.1.1 Skirt/Seal Geometry and Size

The skirt system of surface effect vehicles is usually a three-dimensional configuration with curvature in both the longitudinal and transverse directions. Although significant development efforts on three-dimensional shape prediction methods have been underway in the United States, England, and France, the statement by Mantle, 1975, that there is no adequate theory to predict the geometry of skirts in their three-dimensional form is still valid. Two-dimensional theories coupled with existing craft experience are currently used to design skirts. The major limitations of this approach are two-fold: (1) it can result in overdesign of the systems, and; (2) it can be extrapolated with confidence only to craft of the same size and speed.

Figure 6-1 shows a typical two-dimensional section of a bag-finger skirt. Finger attachments and other design requirements will distort the bag shape, but the geometry can be generated from a succession of constant radius arcs such as that shown. Using simple structural analysis of cylinders, the hoop tension load per unit width in the bag material can be estimated by

$$T = P_b R_1 ,$$

where P_b is the air pressure in the bag, and R_1 is the radius of the bag illustrated in Figure 6-1. However, since this theory does not permit the existence of a pressure gradient within the bag, the tension per unit width is also given by

$$T = (P_b - P_c) \cdot R_2 ,$$

where P_c = cushion pressure

R_2 = radius of another section of the bag illustrated in Figure 6-1.

Ignoring the loads transmitted from the fingers, the bag shape can be determined from the geometrical relationship

$$\frac{R_1}{R_2} = \frac{(P_b/P_c) - 1}{P_b/P_c} \quad (1) .$$

The shape is defined by the ratio of bag pressure to cushion pressure, P_b/P_c. It should be noted that Equation 1 indicates that the shape is not size dependent and can thus be used for full scale as well as model scale vehicles. The loads in the bag are, however, size-dependent. If the cushion pressure increases linearly with the scale factor (λ) and the bag radius also increases linearly by the same scale factor, then the load in the bag increases by λ^2. The material implications of this scaling factor become clear when one considers the following example:

P_b = 50 pounds per square foot

R_2 = 50 feet

T = 208 pounds per inch of width.

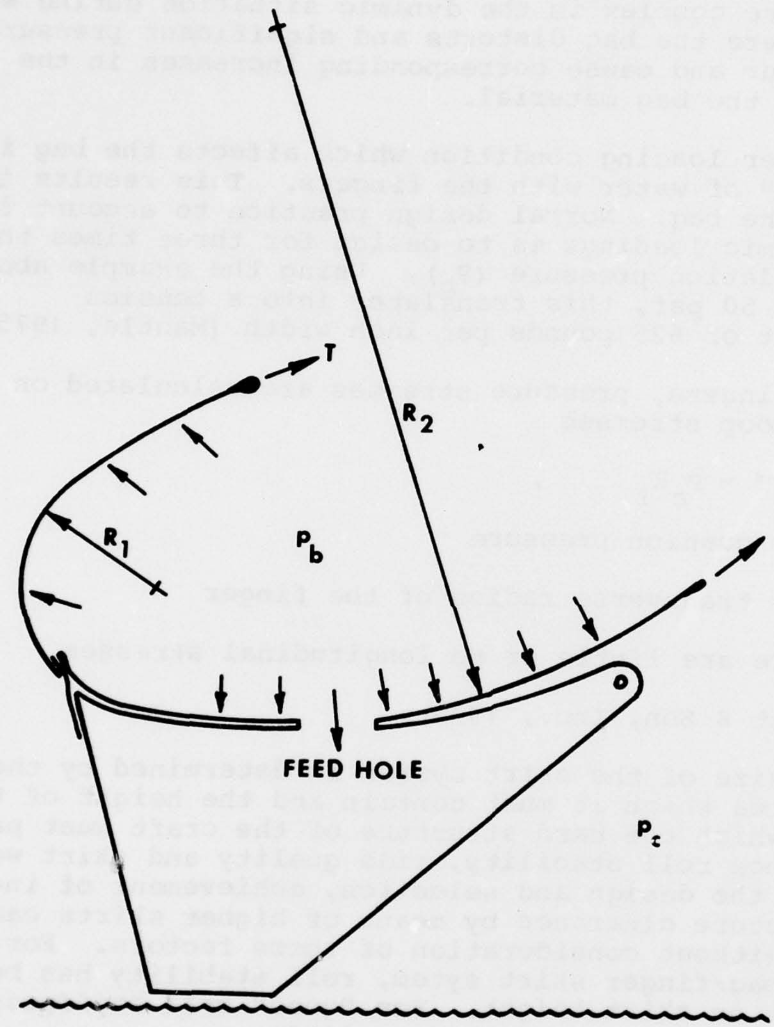

FIGURE 6-1 Two-dimensional bag section (Mantle, 1975).

If P_b and R_2 are doubled ($\lambda=2$), the tension increases fourfold to 832 pounds per inch of width. This geometrical relation applies only in the static case and the situation becomes more complex in the dynamic situation during wave impact, where the bag distorts and significant pressure surges occur and cause corresponding increases in the tension of the bag material.

Another loading condition which affects the bag is the "snatching" of water with the fingers. This results in high loads in the bag. Normal design practice to account for these dynamic loadings is to design for three times the static inflation pressure (P_b). Using the example above where P_b = 50 psf, this translates into a tension requirement of 625 pounds per inch width (Mantle, 1975).

For fingers, pressure stresses are calculated on the basis of hoop stresses

$$T = P_c R_f \quad ,$$

where P_c = cushion pressure

R_f = transverse radius of the finger

since there are little or no longitudinal stresses.

(Rosenblatt & Son, Inc., 1975).

The size of the skirt system is determined by the cushion area which it must contain and the height of the obstacle which the hard structure of the craft must pass over. Since roll stability, ride quality and skirt weight influence the design and selection, achievement of increased hard structure clearance by means of higher skirts cannot be provided without consideration of these factors. For the BHC type bag/finger skirt sytem, roll stability has been the constraint on skirt height. For "good" roll stiffness, the following relationship can be applied:

$$0.10 \le \frac{h}{B} \le 0.20 \quad ,$$

where h = cushion height or skirt height

B = cushion beam or width

(David W. Taylor Naval Ship Research and Development Center, 1975).

This need for height clearance and craft stability must be traded off against the desire to keep the dimensions and weight of the skirt system to a minimum so that the increases in profile drag and craft weight are also minimized (Wheeler, 1974).

More comprehensive methods for determining internal skirt loads are under development. Table 6-1 summarizes the status of these efforts within one major U.S. manufacturer (Bell Aerospace Corporation, 1977).

6.1.2 Materials

There are two aspects of materials which impact on the design process; (1) the nature of the available material and, (2) the performance characteristics of these materials (see also Chapter 3). The need for a strong, flexible material has resulted in the selection of fabric reinforced elastomers (see also Chapters 4 and 5).

Flat sheets consisting of woven fabric coated on both sides with elastomeric layers have been utilized to date. The weaves are essentially two-dimensional, mutually perpendicular configurations. With only flat sheets available, the skirt designer is limited to cylindrical or cone-like shapes in constructing skirt components. This is done so that the component will inflate without distortion.

6.2 Skirt Systems Fabrication

6.2.1 Fabrication Process Selection Factors

The majority of skirt systems in use on SEVs today are fabricated from material that is in the form of a woven cloth coated with an elastomer compound. The most common available widths from suppliers are 36 inches and 54 inches.

Since most of the loads in the skirt are carried by the reinforcing fabric, it is important first, to align the warp or fill direction with the principal load axes and second, to provide a continuous load path between one width of fabric and another. Skirt components are fabricated by bonding the surface coatings together in a simple lap joint, allowing sufficient bond area to transfer tension loads from one piece to another through shear at the interface. This approach has been reasonably satisfactory for moderate loads but with larger craft and higher loads the seam width must increase considerably. Typically, a two-inch seam width is used for materials with a tensile strength of approximately 1000 lb/in.

Seams introduce several problems. If the structure is subjected to loads other than direct tension across a seam, failure may occur by peeling. The increased bending stiffness in the area of seams tends to localize loads, thus

Table 6-1

METHODS FOR DETERMINING INTERNAL SKIRT LOADS
(BELL AEROSPACE CORPORATION, 1977)

STATIC LOAD ANALYSIS PROGRAM

CAPABILITIES:

- ACCOMMODATES A THREE DIMENSIONAL TOROIDAL SHAPE
- NON-LINEAR ORTHOTROPIC MATERIAL PROPERTIES
- NON-LINEAR RELATIONSHIP BETWEEN SKIRT SHAPE, SKIRT LOADS AND WATER SURFACE SHAPE
- GIVES PERIPHERAL AND VERTICAL PLANE LOADS
- INCLUDES LOADS FROM FINGERS (PRESSURE AND DRAG)
- INCLUDES MATERIAL STRAIN EFFECTS ON SHAPE
- INCLUDES BAG AND FINGER MATERIAL WEIGHT
- INCLUDES EFFECT OF SEAMS AND REINFORCEMENT
- INCLUDES "WATER CARRY" EFFECTS

DYNAMIC LOAD ANALYSIS PROGRAM

CAPABILITIES:

- ACCOMMODATES A TAPERED TWO-DIMENSIONAL BAG
- NON-LINEAR MATERIAL PROPERTIES
- NON-LINEAR RELATIONSHIP BETWEEN SKIRT SHAPE, SKIRT LOADS AND WATER SURFACE SHAPE
- INCORPORATES AIR SUPPLY AND FAN CHARACTERISTICS
- HANDLES WAVE IMPACT AND REINFLATION

causing increased surface wear. Areas adjacent to seams also have to flex more than average to make up for the reduced flexibility of the seam, thus accelerating flexural failure. Where panels have seams in two directions, the intersection of the seams presents even greater problems. Generally the joint is configured so that the inner overlapping portions are cut away so that there is still only a maximum of two layers of material at the intersection of the seams.

As craft size increases and single lap joint theoretical widths increase, a practical limit will soon be reached. The distribution of shear stress will become very non-uniform and transfer of loads will be limited. In this case, a different joint configuration will be needed.

6.2.2 Methods of Fabrication

The most common method for construction of flexible skirts has been to join together parts cut from flat sheets. A second method used for fingers is to form a complete seamless unit by press curing between heated, flat platens.

Lamination or the joining of multiple layers of the same material or of different materials is a third means available for fabricating skirt components. Each of these methods will be discussed below.

6.2.2.1 Cut-and-Join Method

After establishment of a skirt geometry, pre-planned panels are cut from the flat elastomer-coated fabric sheets and assembled into skirt components.

The method of joining these panels is largely dependent on the elastomeric coating. Some elastomers such as PVC-nitrile compounds adhere very well to woven fabrics and can readily be bonded with room temperature vulcanizing (RTV) adhesives. For elastomers which cannot be bonded satisfactorily using RTV adhesives, heat and pressure are required for bonding. Details of the bonding processes are discussed below.

<u>Room Temperature Vulcanizing</u>

To make an RTV bond, the skirt component parts are cut out and the seam areas are cleaned by wiping with a clean cloth moistened with methyl ethyl ketone. A severely contaminated surface may require abrading with 60-100 grit emery paper.

The adhesive is mixed and two heavy coats of adhesive are brushed on each seam surface. When the second coat becomes tacky, the surfaces are mated and carefully rolled to eliminate air bubbles, which will weaken a joint. The mated parts must be allowed to cure, preferably under pressure, for a minimum of 8 hours at 75°F to 24 hours at a minimum of 50°F before being moved; the bond reaches full strength after approximately 48 hours. For field repairs, where it is inconvenient to use the normal cure cycle, faster curing may be obtained by heating to a temperature (e.g., 100°F) which is high enough to accelerate curing but not high enough to cause bubbling of the solvent. The above process is typical of the RTV processes in general and applicable to a wide range of formulations.

Hot Bonding

Hot bonding may also be used, as in the manufacture of skirts by the British Hovercraft Comporation. Panels of cured elastomer are assembled with strips of uncured (green) elastomer between the seam surfaces to be bonded. Heat is applied by a press and the green elastomer is vulcanized. While this method does not necessarily provide any greater bond strength than other methods, it is more consistent and less sensitive to variations in operator skill. Skirt repairs can be made in a similar manner using small, portable, electrically heated devices.

The hot bonding process can also be carried out in the autoclave whereby the prepared seams are held in place by vacuum bag pressure. The vacuum bag process can be used without an autoclave, when accelerated cures are not required.

Joints are inspected visually after curing, and defects can often be identified; in some cases, e.g., bubbles or loose edges and joints can be repaired. The general quality of bonding can also be checked by conducting standard peel tests; such tests may reveal variations in the elastomer and adhesive as well as in operator technique and laboratory conditions. A given specimen may or may not be representative of the whole roll, and specially prepared test specimens may not reflect the actual material obtained in the skirt construction. For these reasons, it is advisable to make panels and seams longer than necessary and to check the properties of the trimmings.

R.F. Welding

A completely different joining process that has been used is RF welding. Certain formulations, for example, PVC and polyurethane, generate heat when placed in a radio frequency electrical field because of their dielectric loss characteristics. Simple presses are available with appropriate RF generators that can be fitted with a moveable electrode of any desired shape. By adjusting the intensity of the RF current and the time, any degree of heating may be obtained. Adjustment of the electrode pressure determines the thickness of the welded joint.

The main advantage of this method is that it is virtually instantaneous. The primary disadvantage is that generally only a small area is welded at one time due to the size of available presses.

6.2.2.2 Seamless Press Curing

Small components such as filler pieces to be included in edge beads, etc., can be press cured very conveniently. Larger made-up parts such as "fingers" for the British Hovercraft Corporation type of craft can also be press cured without the need for seams. In fact, the majority of the lower parts of skirts that are designed to be replaceable would probably have greater lives if they were seamless. The most important advantage of this method is that attachments or reinforcements can be built in thereby decreasing the stress concentrations. However, it should be noted that a smooth outer surface obtained by gradually varying the thickness of the elastomer does not necessarily imply the absence of stress concentrations.

The disadvantages of seamless press curing or molding include (1) the considerable expense of making forms or molds for each different type of component, (2) the autoclave required to accept molds of large components, (3) the low rate of manufacture if only one mold is used, and (4) long process times. The general difficulty of designing a complicated mold that can hold all the component parts in the correct relative locations during the cure cycle can limit the usefulness of this approach.

6.2.2.3 Laminating

Since certain areas of skirts are subjected to higher local loads than other areas, higher strength material must be used. The simplest way to obtain higher strengh or greater wear resistance is to add another layer of material. This doubling of the material has proven to be reasonably satisfactory from the point of view of bonding, particularly with PVC-nitrile elastomers. However, it must be remembered that extensions are reduced in these stronger areas and that there will be a tendency for the structure to be distorted in shape. Generally, adding a doubler to the bottom edge of a skirt causes it to curve inward because the material directly above stretches under the influence of the inflation pressures. To prevent a doubler from causing flexural failures in the adjacent material, it is usually given a wavy edge. This helps to prevent the formation of continuous folds along the edges.

In cases where general material strengths have been too low, laminated materials have often been suggested as alternatives. To obtain a material with more nearly isotropic properties, it has also been suggested that several layers of material be bonded with the warp and fill in different directions. This has not generally been successful as the transfer of loads between one layer and the next has caused failures of the bond between the layers.

To obtain greater wear life, many types of wear-surface materials have been laminated to base fabrics. While the normal coating process usually uses just one formulation of elastomer, secondary layers of other formulations have been added at various stages. Generally, if the complete material assembly can be cured at the same time, the various layers blend into one another and form a stronger bond. If secondary coatings are added after the first coating has been cured, or if two layers of previously cured fabric are to be bonded together, it is more difficult to obtain good integrity.

6.3 Reinforcement

The basic reinforcement of the skirt material has generally been a woven nylon fabric, which may vary widely depending on, for example, the type of nylon and the weave. Several different forms of nylon are in existence and the production of the nylon yarns, weaving of those yarns, and all the intermediate processes allow for a wide range of finished products. Details of the fabric manufacture are not usually available to the skirt designer, just as the nylon weaver is usually oblivious of the requirements for skirt materials.

A different type of reinforcement is needed to withstand concentrated loads. Normally, inflation loads are uniformly distributed but eventually are reacted at another part of the skirt or the craft structure through discrete fastenings. In these areas, the loads become more concentrated and special care must be taken to provide proper load paths; specific types of attachment will be described in the next section. Another area that requires reinforcement is around the often large and numerous holes cut to allow or control the flow of air from one part of the skirt to another. The transfer of load through shear around a hole is less efficient in a woven fabric than in an isotropic material, with distances of many hole diameters required before the loading becomes reasonably redistributed. By arranging doublers with their warp and fill directions at an angle to the major load path, the load can be redistributed more rapidly but the loads have to be transferred through the bonded interface and the elastomeric coating. Any weakness here will result in failure of the reinforcing doubler.

Tensile tests of typical panels with holes and doublers show that severe distortions occur before loads can be redistributed; with the warp or fill carefully aligned with the load direction, elongation before failure is typically in the range of 50 - 60 percent. In the bias direction, the elongations are even greater and the strengths much lower.

If more than one row of holes must be cut in a panel, it is best to align them in the load direction, rather than stagger them, so that the number of direct-load-carrying yarns that are interrupted is minimized.

6.4 Attachments

The various parts of a skirt system must be connected to one another and the entire skirt to the craft structure. Although ideally these attachments should be continuous and usually provide an airtight seal, it is also desirable to minimize the number of attachments that have to be disassembled in case of repair or replacement.

Since rigid metal structures can accept relatively high local loads, studs, bolts, rivets, or similar fasteners are very common. When these are used directly with flexible materials, it is very difficult to distribute the load. Thus doublers are usually added to the flexible material and combined with a large rigid member. Loads can most easily be transferred by bonding the fabric to the rigid component over a large area or wrapping the fabric around the part and bonding it to itself. The wrapping technique is preferred in order to obtain a better distribution of the load. Once the load has been transferred from the flexible to the rigid member, then the rigid member can be attached to another rigid member with conventional fasteners. For example, on Aerojet's AALC JEFF (A), the attachments to the hull are all in the form of wrapped bars or rope beads that are trapped by other rigid members to transfer the loads evenly.

On the BHC craft, extensive use is made of piano-type hinges, with individual hinge elements riveted to the skirt edge and to the craft structure. The skirt can then be attached or detached simply by inserting or removing a continuous hinge pin. This sytem allows the attachment to rotate freely rather than having the skirt material bend along a fixed line. In early craft, the continuous flexing of the material along a fixed line was a frequent cause of failure. However, the amount of flexing depends to a large extent on the actual geometry of the particular design.

The piano-hinge concept can also be used to join flexible sections together by utilizing a flexible hinge pin. In some cases zippers have been utilized, but have been found to be too susceptible to the action of dirt when used overland. Lacing has also been used, but the most common method has been to reinforce mating edges and use mechanical fasteners.

6.5 Gaps in Knowledge

The dynamic loads acting on skirts are not known (see also Chapter 3). Additionally, analytical expressions are not available for predicting these loads. As a consequence, procedures are not available for predicting skirt geometry during service.

The relative service life of skirts with elastomer applied by pressure vacuum bag and autoclave curing has yet to be determined conclusively.

It is not known if the seaming and attachment techniques used to date will be adequate for large, high speed SEV's.

6.6 Conclusions

1. The design of skirts for SEV's has yet to be optimized. The optimum design may vary with the vehicle configuration and mission.

2. The interaction of skirt design and materials' requirements is not fully understood. This is due to the lack of availability of procedures for predicting the dynamic loads acting on the skirt and the resulting skirt geometry. A comprehensive, coordinated materials development program involving extensive laboratory testing and field evaluations, as discussed in Chapter 7, would also further understanding in this area.

6.7 Recommendations

1. If double curved skirt designs are to be utilized, contour woven fabric* should be evaluated.

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* Woven Structures, Inc., Division of HITCO.

2. Improved methods for seaming fabric for SEV skirts should be developed and the number of seams reduced. The latter might be accomplished by utilizing wider fabric (See Section 5.2.1) or contour woven fabric.

3. Alternate methods for reducing the stress concentrations in the vicinity of the attachments to the hard structure and around vent holes should be investigated. The use of triaxial woven fabric reinforcement should spread the loads more uniformly into the surrounding material.

4. A long term effort should be undertaken to develop improved procedures for predicting the dynamic loads acting on skirts and the skirt geometry under these loads.

CHAPTER 7

TEST METHODS

7.1 Introduction

Standard laboratory tests can play an important role in the process of improving skirt and seal life, since properly used they may permit selection of optimum materials with a minimum amount of field testing as verification. While this is a goal of laboratory tests, the nature of the materials employed in SEV skirts and the end-use environment are such that failure incidence does not correlate as directly with laboratory test results as is the case with structural metals commonly utilized in the aircraft or ship building industries. This means that for SEV skirts there must be a considerably greater effort devoted to obtaining correlation of laboratory results with field experience than is done for other craft. A similar situation prevails in the pneumatic tire industry, where in many instances a number of laboratory tests are needed for the design and construction of a successful tire. The reason for this is that several possible failure modes can occur in different areas of the tire, and each of the areas has its own individual test or tests which seem to correlate well with service. Thus, one cannot expect that a single test or test method will suffice for the selection of a material for SEV skirt applications. A variety of tests will undoubtedly be required. In order to understand these and their role in the overall picture, a considerable amount of field information must be accumulated, under well documented conditions, and carefully correlated with laboratory test results. Only then, as clear correlations become available, can confidence grow concerning the use of laboratory experiments in material selection.

A study of the available literature (Aerojet General Corporation, 1976; Vosper Thornycroft, 1973; Goodyear Aerospace Corp., 1972, 1973) shows that there are a number of different failure mechanisms commonly encountered in skirt materials (see also Chapter 3). This further reinforces the concept that different tests will be applicable to these different failure modes. As an example of this, large structural tears may very well correlate with either tensile or tear tests of the conventional type, while abrasion or delamination probably will be found to correlate with test procedures different from tensile or tear experiments.

In summary, one may expect at best to find a vector of laboratory test results which must be compared with a vector of field failure experiences. The assessment of the correlation coefficients of this matrix will represent the major task of the experimentalist in future materials selection.

7.2 Modeling and Scaling

The role of modeling and scaling is a natural one to consider for SEV skirts since this type of approach is widely used in the field of aerospace and naval architecture, and is particularly applicable to air cushion vehicles where stability studies are commonly carried out using such techniques. For purposes of scaling skirt materials themselves, the situation is much less favorable, and the general role of modeling needs to be established through additional study. The committee has considered this point and their current feeling is that the modes of failure of skirt materials are so diverse and so poorly understood that it is not possible at this time to employ direct scaling methods to fabricate small scale models of skirt and seal systems which will fail under the same conditions as the full scale systems. The primary reason for this is that it is extremely difficult to geometrically scale textile structures. In order to accomplish this completely, filament size, yarn size, twist, and end count must all be geometrically scaled. This is simply not possible within the realm of practical textile technology available to SEV designers.

Scaling effects do play an important part, however, in the design of suitable laboratory tests for evaluation of materials. The reason for this is that the proper overall ratios of membrane and bending effects must be maintained in many test situations where loads are applied to sample materials in order to measure their characteristics. General practice so far has been to use samples of the same materials used in the skirts for such laboratory testing. In some cases the samples were of relatively small size and loads were applied in such a way that the ratio of membrane to bending forces was quite different in the laboratory specimen as compared with field usage. Under such conditions it might be expected that failure modes would not be the same in the field as in the laboratory, and for this reason care must be used in the design of such tests to maintain the proper ratio of such forces and such stiffnesses in test devices. Only by this means will it be possible to achieve reliable correlation between the modes of failure in the field and in the laboratory.

So far one effort has been made (Hochrein and Thiruvengadam, 1974) to develop dimensionless parameters applicable to skirt material. We believe that the modes of failure of these materials are not well enough defined to be able to use these dimensionless parameters with confidence at this time. Only when the nature of the failure modes becomes clearer can we concentrate on those dimensionless characteristics which are of most importance.

7.3 Standardized Laboratory Tests

A number of standardized laboratory tests have routinely been used to measure the characteristics of skirt materials. Generally these tests have taken two basic forms. In the simplest they are used as a quality control mechanism for assurance that materials are consistent or will meet some quality specification. Such tests are usually rather standard ones whose description can be found in many text books or in appropriate ASTM standards. For example, these are of the character of tensile strength determinations, fabric mass determinations, coating thickness measurements, or possibly tear strength measurements. Such tests are well known in the rubber and textile industries.

The second major use of these tests on coated fabric materials has been to measure properties which have importance to the longevity of skirt materials for SEV craft. This is a difficult job at best, since at the present time one is forced to guess the relationship between specific tests and the loading conditions on the craft. The primary tests and measurements used for this type of service have been the following:

- Coating thickness and coated fabric thickness
- Fabric weight, coating weight, and total weight
- Elongation in both warp and fill directions
- Tensile strength in both warp and fill directions
- Coating adhesion
- Tear strength in both warp and fill directions
- Cyclic tensile fatigue
- Modulus
- Aging resistance
- Resistance to sea water
- Fuel and ozone resistance
- Resistance to flame

- Brittleness temperature
- Flex resistance (De Mattia)

A number of these tests are described in the ASTM standards and are common tests in the rubber industry. Generally speaking the quality and number of these tests have been improving, and skirt fabricators are becoming more sophisticated in their use to screen various materials for SEV service. In the case of arctic operation these tests should also be performed at low temperatures. In all cases the tests should be applied to wet fabric as well, preferably fabric which has been allowed to soak with exposed ends in sea water for a fairly long period of time. The reason for this is that service experience indicates that it is impossible to prevent wicking of water through the fabric due to wear of the skirt materials at the edges where they contact the ground or the sea. This means that water inevitably permeates into the fabric and service life may be affected. This should be an important factor in the choice of the optimum skirt materials.

7.4 Specialized Laboratory Tests

7.4.1 Introduction

A number of specialized laboratory tests have been devised for evaluating the service potential of candidate skirt materials. In general, these are small scale, low cost evaluations when compared with the alternative of screening candidate materials in the end-use application. Ideally these specialized tests should induce the same types of damage and failure as are experienced under service conditions; they should correctly rank the materials for useful service life; and the laboratory test data, when correlated with service performance should permit reasonable predictions of service-life expectancy.

Throughout the history of skirt materials development, laboratory evaluation techniques have evolved into three major categories of tests:

- Physical properties of the fiber, fabric, adhesive and rubber coating (static tests)
- Flexibility and fatigue properties of the skirt material (dynamic tests)
- Wear resistance measurements of the skirt material (dynamic tests)

The first is a series of tests to evaluate tensile strength, tear strength, and peel strength of the material.

Each material component (fiber, adhesive, and coating) is evaluated individually as well as the overall material system. The tests are often run under standard ASTM specifications and the results are used predominantly for quality control purposes.

Flexibility and fatigue properties can also be measured by tests which are relatively well known, and are used in a variety of industries. However, these tests tend to be somewhat more specialized in nature, and are often modified for specific product applications. Finally, in the third category, wear tests are used in both the textile and the pneumatic tire industries, but again many tests exist and none correlate well with end use performance so no really adequate single test can be specified as the best.

Laboratory test devices used to evaluate candidate skirt materials are described below.

7.4.2 Laboratory Test Devices

Abrasion and Wear Tests

Some limited wear resistance evaluations have been made to compare wear-life of candidate materials. These tests have been run on a standard or modified Tabor wheel abrader. In this test, a flat piece of material is rigidly mounted to a horizontally rotated specimen holder and an abrasive wheel is vertically rotated against the specimen. The data obtained is simply the wear rate, or the material removed over a given period of time. One series of abrasion tests of representative finger materials (Tennyson and Smailys, 1977) showed that abrasion resistance increased significantly with decreasing temperature. In general, abrasion test data have not been related to service life.

Impact Test Devices

The principal laboratory test devices developed for simulating finger impact with debris and obstacles are the rod impactor and the belt impactor.

The rod impactor (see Figure 7-1) reported by Goodyear Aerospace Corporation, 1972, consists of beater-rods attached to a variable speed rotating shaft which strike candidate finger specimens. The finger specimens are generally stabilized by simulated cushion pressure and the test variables include impact speed, relative geometry of beater-rod and finger model, and temperature. The primary mode of failure is abrasion of the elastomeric coating in the area of impact. A major deficiency of this device is that it produces essentially a point, or line impact on the finger specimen whereas the impacts received by a finger in

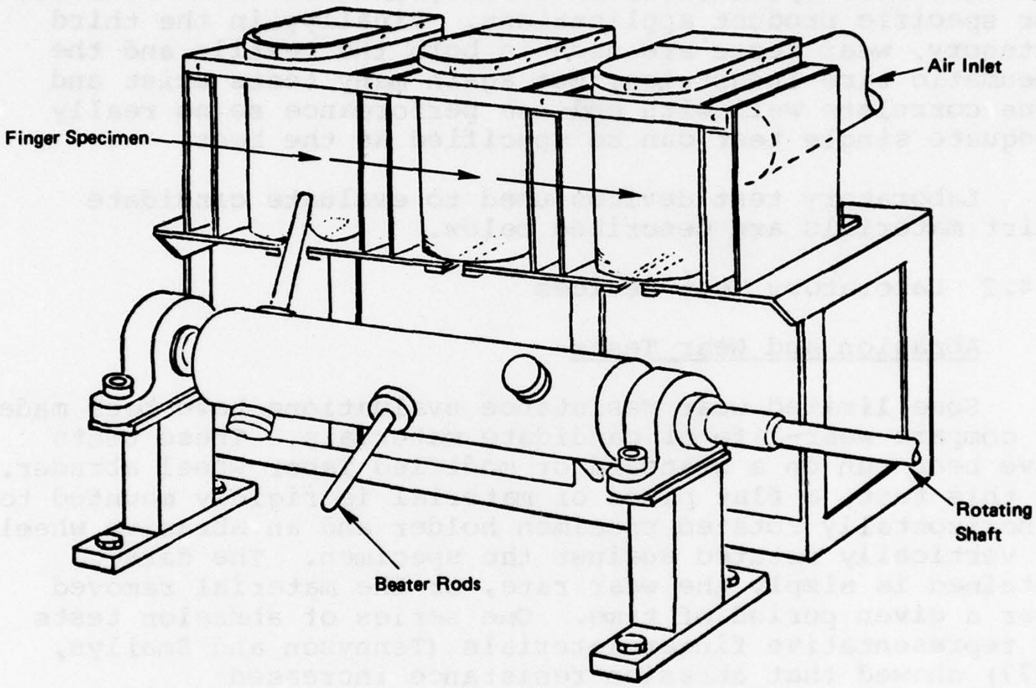

FIGURE 7-1 Goodyear rod impactor (Goodyear Aerospace Corporation, 1974).

service are usually due to obstacles which are wider than the fingers and which may produce a different failure mode. In addition, heat generated in the specimen due to rate and severity of impact may distort the test results.

The belt impactor shown in Figure 7-2, and reported by Kelly et al., 1976,consists of a variable-speed belt on which is mounted an impacting object which strikes the candidate finger specimens. The finger specimens are small-scale cylinders stabilized by cushion air. The shape, width, and height of the impacting objects, and the geometry of the specimens can be selected to simulate on a small scale the conditions a finger would experience in service. The effect of adjacent fingers can also be simulated. Test variables include impact speed, relative geometry, and temperature. The primary mode of failure in a test cycle reported by Hochrein and Thiruvengadam, 1974, was abrasion of the coating, followed by tearing of the fabric at fold areas generated at the outer front edges of the cylindrical specimens after initial impact. The tearing of the fabric appears to be directly related to the cylindrical geometry of the test specimen, indicating a basic deficiency of this device, unless non-cylindrical specimens are used. Another major deficiency of this device is the possible buildup of heat generated by the high frequency of impact, which may distort the test results. (So far, the belt impactor test is believed to provide the better simulation of the two). (See Section 3.2.2.4).

Air Flagellator

The air flagellator uses high velocity-air flow to induce rapid flag-like flapping of a flat-sheet material specimen which is rigidly supported at the leading edge. In the British Hovercraft Corporation (BHC) version (Figure 7-3) a blower forces air through a rectangular channel approximately 4 inches high by 16 inches wide at a velocity of about 200 feet per second. The test specimen, approximately 16 inches wide by 25 inches long, is bolted at one end at the blower exit and allowed to flap in the wind stream as a flag might do, the other three sides of the specimen being free. Water spray is introduced through small holes in a pipe at the fixed end of the specimen. The motion of the specimen appears to be random in nature. BHC reports that a material satisfactory for Hovercraft service loses 1 to 3 percent by weight in this test in two hours. The failures induced are almost exclusively edge fraying following delamination, and the specimens from this test appear exactly the same as worn skirt materials. BHC reports that materials that rank poorly in this test usually do poorly in service, and materials that rank well in this test may or may not do well in service. They feel that the best method of material selection is the use of this test

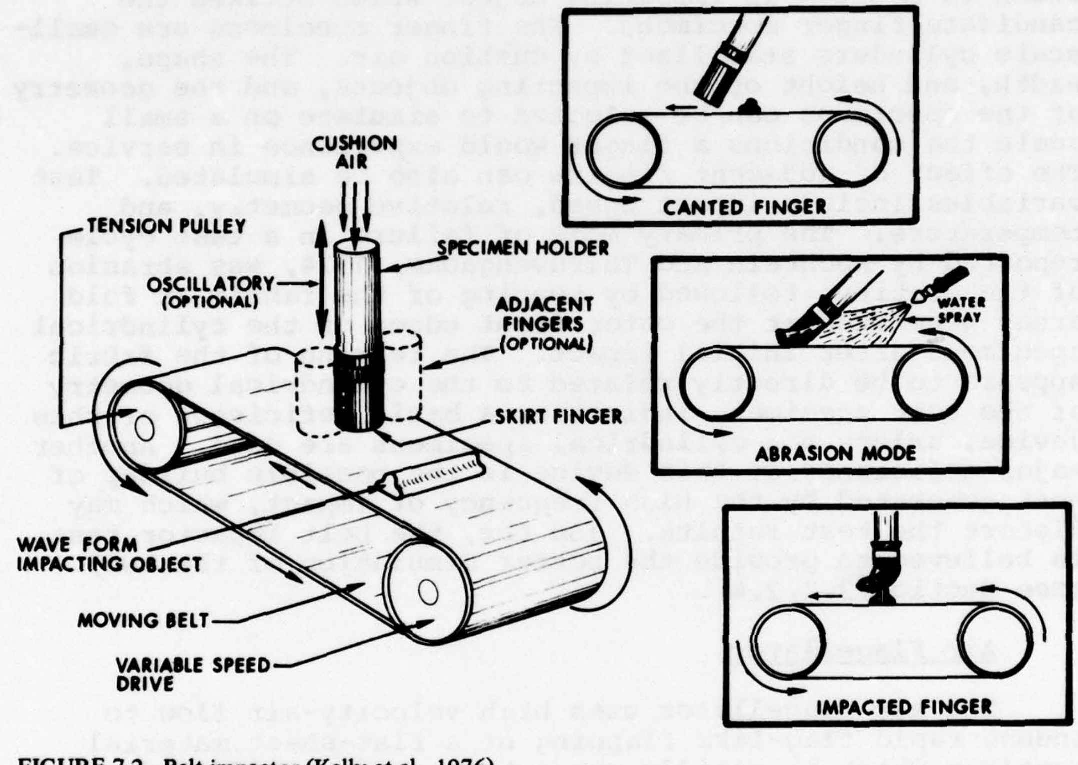

FIGURE 7-2 Belt impactor (Kelly et al., 1976).

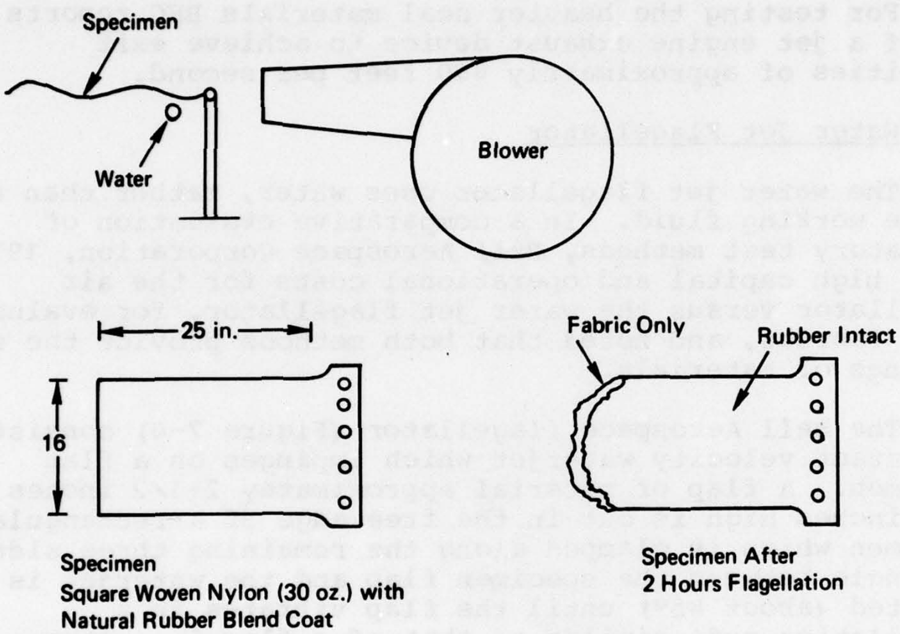

FIGURE 7-3 Air flagellator (BHC).

coupled with field experience. In a well planned experimental investigation of finger wear in service on an SR.N5 hovercraft, Swallow et al., 1971, reported very high correlation between wear rate and air flagellation test results. In summary, this air flagellator appears to be a very useful tool for screening candidate materials.

For testing the heavier seal materials BHC reports the use of a jet engine exhaust device to achieve exit velocities of approximately 400 feet per second.

Water Jet Flagellator

The water jet flagellator uses water, rather than air, as the working fluid. In a comparative evaluation of laboratory test methods, Bell Aerospace Corporation, 1973, cited high capital and operational costs for the air flagellator versus the water jet flagellator, for evaluating heavy fabrics, and noted that both methods provide the same rankings of materials.

The Bell Aerospace flagellator (Figure 7-4) consists of a constant velocity waterjet which impinges on a flat specimen. A flap of material approximatey 2-1/2 inches wide by 2 inches high is cut in the free edge of a rectangular specimen which is clamped along the remaining three sides. The angle between the specimen flap and the waterjet is adjusted (about 45°) until the flap vibrates in a flagellation mode similar to that of a flag in a strong breeze. The very small test specimen size suggests that the flexing modes may be a strong function of the material flexibility, and that some tailoring of the test geometry may be required to achieve the desired flagellation response particularly for stiff specimens.

The Goodyear Aerospace Corporation pulse jet flagellator (Figure 7-5) uses a high-velocity water nozzle interrupted by a rotating disc containing an opening to deliver pulses of water to the front of a test specimen at a selected velocity ranging up to 100 knots. The test specimen, configured in a half cylinder approximately 8 inches in diameter and 10 inches long, is held at an angle of 18 degrees from the vertical and is stabilized by simulated cushion-pressure on the inner surface. This modifed water jet flagellator appears to simulate repeated wave impact, on the test specimen, with a vigorous flapping and return of the specimen to its original stabilized shape between impacts. Two types of failure are induced: body failure of the elastomeric coating at or near the point of impact, and edge failure similar to that induced by the air flagellator. Test data on flagellator failures indicates that for a given velocity, edge failures occur earlier than body failures. It therefore appears that this test should

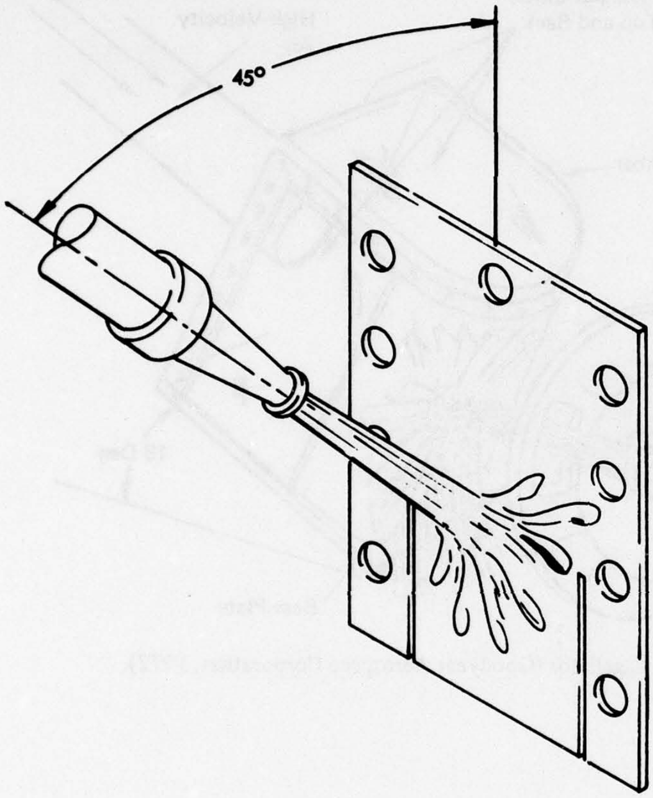

FIGURE 7-4 Original flagellator test sample and jet location (Goodyear Aerospace Corporation, 1972).

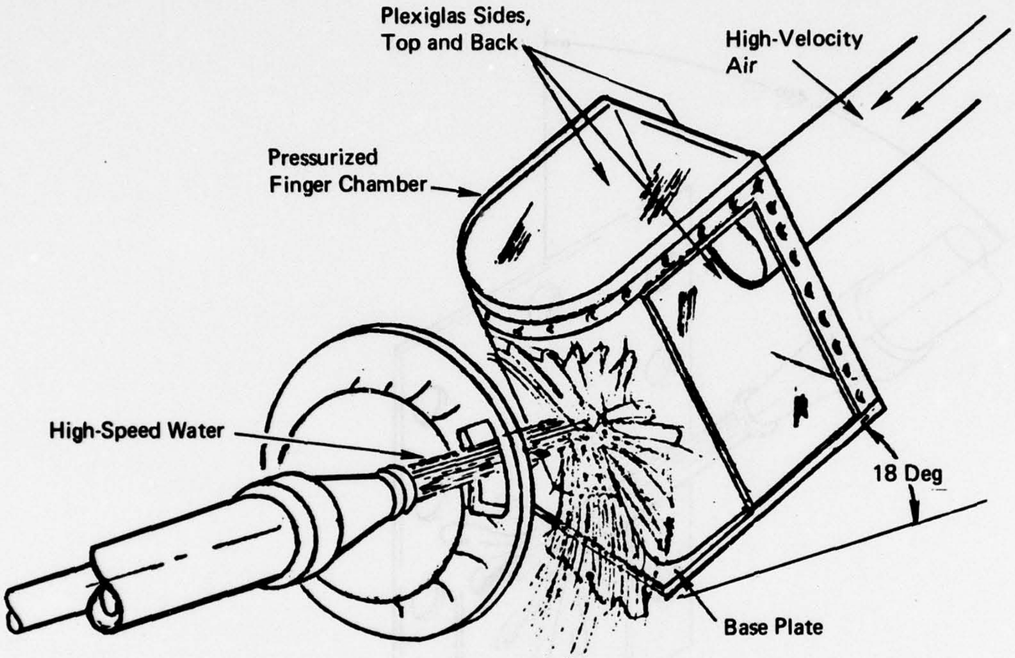

FIGURE 7-5 Modified GAC pulse jet flagellator (Goodyear Aerospace Corporation, 1972).

be able to provide a ranking of materials that is the same as that provided by the Bell Aerospace water jet flagellator and by the BHC air flagellator.

Large Test Devices

In a proposed Navy Seal Test Rig, a full-scale finger would be mounted to a frame on actuators in an air plenum, and stabilized as in service by an air supply. An adjustable 3 inch deep high-velocity flow of water is directed at the lower leading edge of the finger. Actuators on the fingerframe and on the water-channel mechanism provide geometric flexibility for varying the depth of water loading on the finger. This seal material test rig was designed to simulate service conditions on full-scale hardware in the laboratory. Until test data becomes available, the merits of this particular device cannot be determined.

An environmental test rig has been developed by the Rohr Corporation in San Diego, which uses a horizontal water jet directed against a coated fabric sample representative of the skirt material as used in a typical craft. This is a relatively high velocity jet and causes quite rapid degradation of the coated fabric sample and appears to provide some degree of correlation with service experience.

Bell Aircraft Corporation in New Orleans has developed a water wheel type of test device, using an enclosed cylinder mounted on a vertical axis. The cylinder is spun at high speed with water inside, and the water moves outward to form a relatively thin film along the inside surface of the drum. A test specimen is brought into contact with the high velocity water film and tends to oscillate due to the naturally unstable elastic deformation which it exhibits. This type of oscillatory hydrodynamic contact can cause material degradation and failure, and the system might act as a screening device for coated fabric materials for use in SES craft skirts.

A test device for low friction coatings has been developed at Renssalaer Polytechnic Institute. This device shown in Figure 7-6 uses an inflated innertube-like specimen of toroidal shape which is rotated while simultaneously being loaded against a test surface. It evaluates both wear and frictional characteristics of the coated fabric materials being tested.

7.4.3 Material Considerations in Specialized Laboratory Tests

Textile-elastomer composites possess certain properties which make it particularly difficult to adapt small scale

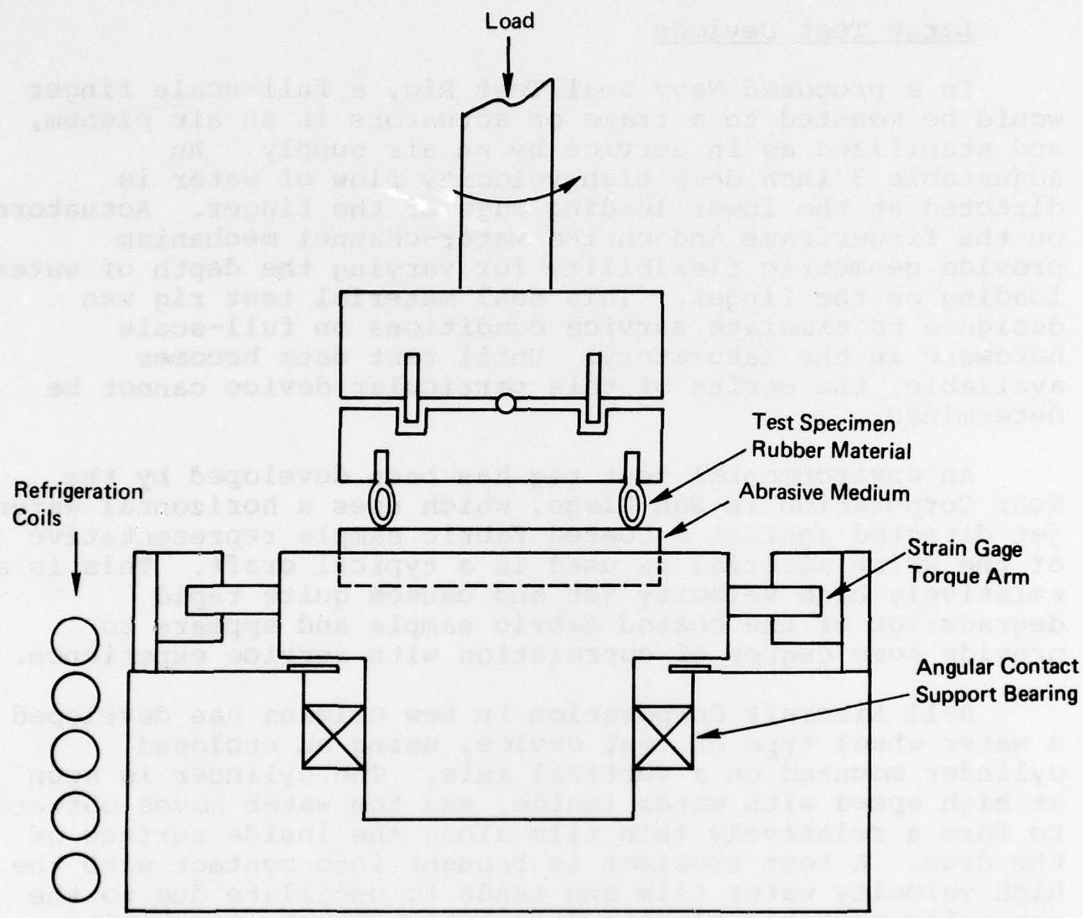

FIGURE 7-6 Coated skirt test device (U.S. Coast Guard, 1976).

accelerated laboratory tests to evaluate larger scale products in service. Among these difficulties is the problem of insuring adequate distributions of bending and membrane stresses in small scale models of larger scale pneumatically stiffened structures. Secondly, the role of accelerated testing in textile-rubber composites is poorly understood, and the influence on fatigue life of stresses higher than service stresses is not at all clear in a general way. Therefore it is not possible to say quantitatively what the service life of a given part will be from performance in the laboratory. Finally, textile-rubber composites suffer significantly from internal heating due to the "lossy" character of the textile and particularly the rubber component. Temperature buildup is a well known phenomenon in normal textile-rubber structural applications, such as pneumatic tires or power transmission or conveyor belting. While in metallic products the levels of temperature obtained would not be serious, in textile-rubber composites these temperature rises may be and often are sufficient to substantially degrade the fatigue life of the product. The difficulty encountered here in assessing the value of the laboratory test is simply that accelerated testing in the laboratory may, and in fact often does, induce a higher temperature level than the field service. In this case it is even more difficult to assign quantitative values to laboratory results which have meaning in real products. Even more serious, rank orders may reverse from laboratory test conditions to field experience. This means that the use of small scale accelerated laboratory experiments is a very difficult and uncertain approach. There is no hope of achieving success with it until definite field measurement data is available on the operating severity of the stress state in the full size product operating in its real environment.

7.5 Field Measurements

So far only very few field data have been available on measured characteristics of the fabric materials under actual operating conditions. Such measurements are admittedly difficult to make. Instrumentation for the measurement of textile forces or strains is not commonly available on a commercial basis, and most of it must be custom designed for the particular fabric and application at hand. In addition, the difficulties of attaching sensors and maintaining lightweight lead wires under a very severe vibration environment present a real challenge to the instrumentation engineer in the acquisition of such data. Nevertheless the data is vitally needed in order to be able to design specialized laboratory tests which are compatible with and reproduce accurately the conditions met in the field.

The types of measurements which appear to be most achievable here are textile cord loads, fabric strains and fabric accelerations. Each one of these three would be of considerable value in the construction of specialized laboratory tests, since they would allow matching of the laboratory test with actual operating forces.

The measurement of direct textile cord loads can probably best be carried out on bag materials. Usually bag materials are substantially heavier than finger materials, cord diameters are larger, and in these cases it is somewhat easier to solve the problem of lead wire flexure and breakage. Well known methods are available for the measurement of cord loads under such situations (Clark, 1970; Clark and Dodge, 1972; Walter, 1972, etc.). By the proper use of instrumented textile cords it should be possible to obtain information on the magnitude of cord forces in bag materials under normal operating conditions, and in particular to examine the forces associated with the rather unusual situations of wave impact which may occur in heavy seas. In addition, such instrumentation devices should be of general use in the acquisition of cord force information in the vicinity of areas which tend to cause structural stress concentrations, such as around feed holes and attachments.

In the general area of the SEV finger, the acquisition of cord load data may not be as feasible, since it will be more difficult to instrument individual cords in the square woven fabrics commonly used for such service. Here a better approach might be the direct measurement of fabric strains. The committee feels that work on the measurement of fabric strains has probably developed further in England than any other place, as exemplified by the symposium on the subject at the Shirley Institute, 1973. In addition, British Hovercraft Corporation has carried out extensive efforts to measure fabric strains directly over the past several years. The committee feels that this work should be carried forward since it is very close to fruition at this time. Only minor improvements in the instrumentation and lead wire technique will be needed in order to obtain rather satisfactory field data on fabric strains in skirt materials.

Finally, attempts have been made to measure accelerations on skirt materials during their flutter or flagellation modes (British Hovercraft Corporation, private communication). While this information is not as valuable as direct loads or strains, it still represents an improvement over what is currently available since it should allow correlation between the air or water flagellation test devices now in use, and operating conditions. This should permit the design of more accurate test methods.

Small, lightweight accelerometers are currently available commercially, and their lead wire systems need only be refined to the point where they can last over an acceptable period of time so significant amounts of information can be obtained from operating craft. This is the type of measurement which should be pursued diligently.

As in similar vehicles, the loading spectrum for SEV seals and skirts is random in nature, and will require statistical definition. It has not yet been well characterized. It therefore appears that as of now a clear link does not exist between laboratory evaluation of materials and their subsequent service life.

7.6 Gaps in Knowledge

The major areas of quantitative uncertainty now seem to be:

(a) Lack of field data

(b) Lack of complete understanding of the primary failure modes of the materials

(c) Lack of correlation between service life and laboratory experiment

7.7 Conclusions

1. The acquisition and testing of adequate SEV skirt materials has so far been a fragmented process with each individual builder of craft carrying out his own program. This has led to a relatively inefficient development effort for such materials since only a small portion of the total engineering effort in the design of each craft has been assigned to this task. This fragmented situation continues to exist.

2. Few actual quantitative or numerical field data have been obtained for the types of environments experienced by SEV skirt materials.

3. While visual examination of failure phenomena in skirt materials has been carried out, little serious effort at detailed microscopic and nondestructive examination methods has been applied to the failure examination problem.

4. The air flagellator and the water flagellator are relatively simple laboratory test techniques which induce the same mode(s) of failure that are experienced in service, and which provide a reasonably good qualitative ordering of candidate materials. These techniques can be used to induce failure in the laboratory more rapidly than occurs in

service. Empirical coefficients are therefore needed to make quantitative predictions of service life on the basis of laboratory test data, and these coefficients must be based on a statistically significant sample of laboratory test and service life data. The Swallow et al., 1971, report showed a high correlation between service wear rate and air flagellator laboratory test results, thereby demonstrating that this may be a viable approach.

7.8 Recommendations

1. A single organization should be made responsible for the specification and acquisition of field data, for the correlation of field data with conventional laboratory experiments, and for recommendation of the modification or redesign of the specialized flagellation tests which currently exist based on correlation of field data with laboratory test results.

2. Field data should be acquired, preferably on a statistical basis, using either available craft or a craft dedicated to studies on skirt and seal materials.

3. A detailed phenomenological study should be carried out on the failure phenomena currently experienced by existing SEV materials. This might be accomplished by optical and scanning electron microscopic studies or by nondestructive test techniques.

4. Typical mission profile data should be acquired, including data on the fabric loads and strains experienced by both bag and finger materials. Such information is badly needed for correlation of field service data with failure modes.

5. The committee concludes that the development of new or additional tests is not called for at this time. Rather, what is needed is a better understanding of existing tests and a better understanding of service operating conditions. Given those, we feel it is very probable that existing tests can be made to reflect much better the true service experience of the SEV.

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