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TECHNOLOGY ASSESSMENT OF AUTOMOTIVE APPLICATIONS OF METAL-PLASTIC LAMINATES

Volume II

Robert Kaiser

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Winchester, MA 01890

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AUGUST 1980
FINAL REPORT

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16. Abstract

An analysis is presented of the potential use of metal-plastic laminates in automotive structures based on the relative physical properties and costs of laminates to steel, and on the compatibility of the laminates with current automotive manufacturing practice. Laminate cost/weight and manufacturing analyses were performed on selected components from a passenger automobile and light duty truck. There are a number of small, non-visible, functional components currently made with steel sheet that would be likely candidates for laminate use.

The current commercial status of metal-plastic technology is reviewed, and the potential automotive use of laminates over the next decade is assessed. It is projected that laminates will not have a measurable impact on the fuel economy of U.S. production automobiles at least through 1990.

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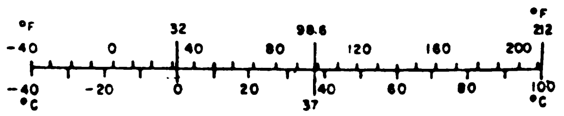
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

PREFACE

This analysis was performed to assess the technology and the long term impact of metal-plastic laminates on automobiles for DOT/National Highway Traffic Safety Administration, Office of Passenger Vehicle Research.

The study was conducted under sub-contract to Corporate-Tech Planning, Inc., 275 Wyman Street, Waltham, MA, as part of Contract No. DOT-HS-9-02110, entitled "Review and Evaluation of Automobile Fuel Conservation Technologies". Two case study analyses were performed as part of this study by Pioneer Engineering and Manufacturing Company, 2500 E. Nine Mile Road, Warren, MI 48091. In these case studies, likely applications of metal-plastic laminates on two representative motor vehicles were identified, and the effect of metal-plastic laminate substitution on the cost and weight of a selected number of components was then analyzed.

The assistance and guidance of Mr. William Basham, Technical Monitor for NHTSA, and Mr.Theodore Taylor Jr., CTP Program Manager, in the execution and completion of this study are gratefully acknowledged. The help and support of Messrs. Norman Ludtke, Henry Kaminski, Jack Gilmore, and of Ivan Shadko of Pioneer in the development of the case study analyses, added substantially to the content of this report.

During the course of this study, discussions and exchanges of views were maintained with many members of the technical community that had an interest in the various facets of the technology of metal-plastic laminates, as listed in Appendix A. The help and cooperation of all concerned is also gratefully acknowledged.

Robert Kaiser
Argos Associates, Inc.
Principal Investigator

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LIST OF SYMBOLS

A_1	Calculated Part Area
AA	Aluminum Alloy
AK	Aluminum Killed
B	Buckling Resistance
C	Crippling Resistance
°C	Degree Centigrade
D	Denting Resistance
DOT	Department of Transportation
E	Tensile Modulus = Flexure Modulus
E^*	Effective Flexure Modulus
E_a^*	Apparent Flexural Modulus
E_{sl}	In-plane Stiffness of a Laminate
ECC	Electrolytic Chrome Coated
F	Flexural Strength
F^x	Vibration Frequency
°F	Degree Fahrenheit
G	Shear Modulus
GPa	Giga-Pascal
I	Moment of Inertia
J	Joule
HD	High Density
Kcal	Kilo-calorie
Kg	Kilogram
L	Local Buckling Resistance
LD	Low Density
LDR	Limiting Draw Ratio

LIST OF SYMBOLS (Cont.)

M	Bending Moment Resistance
M^F	Bending Moment Resistance in Fatigue
MPa	Mega-Pascal
N	Newton
$\bar{N}$	Shear Deflection Factor
NARI	National Association for Recycling Industries
NHTSA	National Highway Traffic Safety Administration
P	Applied Vertical (end) Load
PBT	Polybutylene Terephthalate
PET	Polyethylene Terephalate
S	Stiffness
S^b	Bending Stiffness
S^t	Torsional Stiffness
SAE	Society of Automotive Engineers
Tg	Melting Temperature (amorphous)
T_m	Melting Temperature (Crystalline)
T_{max}	Maximum Air Temperature in Paint Bake oven
T_{min}	Minimum Temperature
V	Shear Force
W	Weight per Unit Area
W_p	Part Weight
Y	Stress Yield Factor
b	breadth
cm	centimeter
db	decibel

LIST OF SYMBOLS (Cont.)

h	dent depth
hr	hour
in.	inch
k_B, k_s	beam loading constants
lb	Pound
m	meter
mm	millimeter
s_c	shear stress in core
t	thickness
y	total deflection
α	Core Volume Ratio
$(\dot{\varepsilon})$	strain rate factor
ν	Poisson's Ratio
ρ	density
σ	ultimate tensile strength
σ^F	fatigue strength
σ_C	compressive stress
σ_{sl}	inplane strength
σ_y	tensile yield strength
σ_{yaf}	apparent value of yield strength of face sheet
σ^*_c	tensile strength of core at laminate yield point
σ^*_f	tensile strength of face sheet of laminate yield point
L	refers to laminate property (subscript)
c	refers to core property (subscript)
f	refers to facing property (subscript)

LIST OF SYMBOLS (Cont.)

subscripts	
n	new material
o	original material
s	refers to steel property
superscripts	
n	geometrical constant
o	Degree

2.0 MATERIAL PROPERTIES AND WEIGHT SAVINGS POTENTIAL OF METAL PLASTIC LAMINATES

2.1 CHARACTERISTICS OF METAL-PLASTIC LAMINATES CONSIDERED IN STUDY

The metal-plastic sandwich laminates that are the focus of the present study are thin sandwich structures that have external metal facings bonded to a thermoplastic polymer core. The laminates of interest are typically less than 2.5 mm (0.100 in.) thick. The component materials of the laminates currently being considered for automotive use are listed in Table 2-1.

The metal facings being considered are all commercially available sheet metals and the thickness of the facings will vary with the design of the laminate and its intended use, but for many applications sheet facings will range from 0.13 mm (0.006 in.) to 0.25 mm (0.010 in.) in thickness. These gauges are typical of the sheet metals now used by the can industry.

The polymer cores being considered are principally polyolefins because of cost considerations, though one developer, Monsanto Company is promoting the use of nylon 6-6, a more costly material that has better performance characteristics. Representative properties of materials of interest are summarized in Table 2-2.

A third material that is sometimes required is an adhesive which bonds the polymer core to the face sheets. In some systems, the polymer and/or the face sheets are treated in such a manner as to render the polymer self-adhering to the face sheets, so that a third component is not required. In other laminates, a separate adhesive is required and is applied usually to the face sheet during the fabrication process. The adhesive is usually a dispersion of a modified polymer similar to the core material in a soluble solvent. These adhesives are usually proprietary formulations.

The general characteristic of the laminates of interest is that these materials are designed primarily to replace sheet steel in applications where rigidity is the design constraining criterion. These laminates, therefore, are designed to have a lower weight per unit area than the sheet steel that would be replaced while exhibiting equivalent rigidity. Because of fabrication requirements, the laminates also have to be formable by standard sheet metal working processes.

Laminates specifically designed for their sound damping properties were not included within the scope of the present study. These laminates consist of two fairly thick face sheets bonded by a fairly thin visco-elastic core. These laminates are designed to reduce a noise and vibration from resonating panels,

TABLE 2-1

METAL-PLASTIC LAMINATES CURRENTLY BEING CONSIDERED FOR AUTOMOTIVE USE

FACE SHEETS

- Aluminum Killed (AK) Low Carbon Steel - Black Plate D
- Electrolytic Chrome Coated (ECC) Steel
- Aluminum Alloys

CORE MATERIALS

- Polyethylene
- Polyethylene Co-polymer, self-bonding
- Polypropylene
- Polypropylene Co-polymer, self-bonding
- Polypropylene, Talc Filled
- Nylon 6-6
- Polyionomer

ADHESIVES

- None
- Proprietary Formulations

TABLE 2-2

REPRESENTATIVE PROPERTIES OF POLYMERS OF INTEREST

		NYLON 6-6		POLYETHYLENE			POLYPROPYLENE			POLYIONOMER
	ASTM TEST METHOD			LOW DENSITY	HIGH DENSITY	ETHYLENE-VINYL ACETATE - CO-POLYMER	HOMO POLYMER	CO-POLYMER-	40% TALC FILLED	
Specific Gravity	D792	1.13 - 1.15		0.910-0.925	0.941-0.965	0.92-0.95	0.900-0.910	0.890-0.905	1.23-1.27	0.93-0.96
Melting Temperature, °C										
Tm (crystalline)		265				65-90				90-96
Tg (amorphous)				95-130	120-140		168	160-168	158-168	
Mechanical Properties										
Tensile Strength at Break, psi	D638	12,000[b]	11,000[c]	600-2300	3100-5500	1400-2800	4500-6000	4000-5500	4300-5000	3500-5000
Elongation at Break, percent	D638	60[b]	300[c]	90-800	20-130	550-900	100-600	200-700	3-8	350-450
Tensile Yield Strength, psi	D638	8,000[b]	6,500[c]	800-1200	3000-4000	--	4500-5400	3500-4300		
Tensile Modulus, 10^3 psi	D638			14-38	60-180	20-120	165-225	100-170	450-575	20-60
Flexure Strength (rupture or yield) psi	D790	17,000[b]	6,100[c]	--	--	--	6000-8000	5000-7000	8500-9200	
Flexural Modulus, 10^3 psi										
@ 73°F	D790	420[b]	185[c]	8-60	100-260	1-20	170-250	130-200	450-625	30-50
@ 200°F	D790						50	40		
Izod Impact - ft-lb/in of notch	D256A	0.8 - 1.0[b],	2.1[c]	No break	0.5-20	No break	0.4-1.0	1.0 - 20.0	0.4-0.6	6-15
Other Properties										
Coefficient of Linear Thermal Expansion 10^{-6} in/in/°C	D696	80		100--220	110-130	160-200	81-100	68-95	55-80	120
Deflection Temperature Under Flexural Load °F										
@ 264 psi	D668	167		90-105	110-130	93	120-140	115-140	180-270	100-120
@ 66 psi		474		100-121	140-190	140-147	225-250	185-220	265-290	
Thermal Conductivity 10^{-4} Cal-cm/sec-cm^2 - °c	C177	5.8		8	11-12	--	2.8	3.5-40	7.6	5.8
Water Absorption in 24 hrs, Percent	D570	1.0 - 1.3		<0.01	<0.01	0.05-0.13	0.01-0.03	0.03	0.01-0.03	0.1-1.4

a) Source: Modern Plastics Encyclopedia 1979 - 1980 Edition (Ref 2-1)

b) Dry, as molded (0.2% moisture content)

c) Condition to 50% relative humidity

and do not offer any significant weight savings over steel. Manufacturers of heavy duty transportation equipment where noise is a serious problem are very interested in sound damping laminates for a variety of brackets and enclosures. Respresentative commercial sound damping materials are U.S. Steel's "Nexdamp" and Specialty Composites Corporation's "Tufcoate." Sandwich laminates considered within the context of the present study were also limited to symmetrical laminates with identical facings--each of the same material and same thickness. It should be noted that bonding two different metal sheets to a polymer substitute can be accomplished as readily as bonding of two sheets of the same material. However, from the point of view of the development of the technology, unsymmetrical laminates represent a second order refinement which one would consider for a specific application after having first considered a symmetrical laminate.

The metal-plastic laminates of interest to the present study are a special class of structural sandwiches.

The American Society for Testing and Materials (ASTM) defines a structural sandwich as a construction comprising a combination of alternating dissimilar simple or composite materials, assembled and intimately fixed in relation to each other so as to use the properties of each to specific structural advantages for the whole assembly. As was shown in Figure 1-1, these metal-plastic sandwich laminates combine thin, strong, stiff, hard, but relatively heavy metal facings with a thick, relatively soft, light, and weaker plastic core in a manner that results in a lightweight composite that is stronger and stiffer in many respects than the sum of the comprised material.

Taken separately, the thin metal face sheets of the laminate are easily bent and the plastic core is easily broken. However, when these face sheets are bonded to opposite faces of the plastic core the resulting sandwich strongly resists bending.

As indicated by Figure 2-1, the basic principle of sandwich laminate construction is much the same as that of an I-beam, which is an efficient structural shape because as much of the material as possible is placed in flanges situated farthest from the center of bending or neutral axis. Only enough material is left in the connecting web to make the flanges act in concert and to resist shear and buckling. In a sandwich laminate, the facings take the place of the flanges and the core replaces the web. The difference between the two structures is that, in an I-beam, the web is narrow and consists of the same high modulus material as the flanges, whereas in a sandwich laminate the core is that of equal area as the face sheets, but is of a different material which has a much lower modulus. The facings act in concert to form an efficient internal stress couple or resisting moment counteracting the externally imposed bending moment. The core resists the shear stresses set up by the external loads and stabilizes the face sheets against wrinkling or buckling

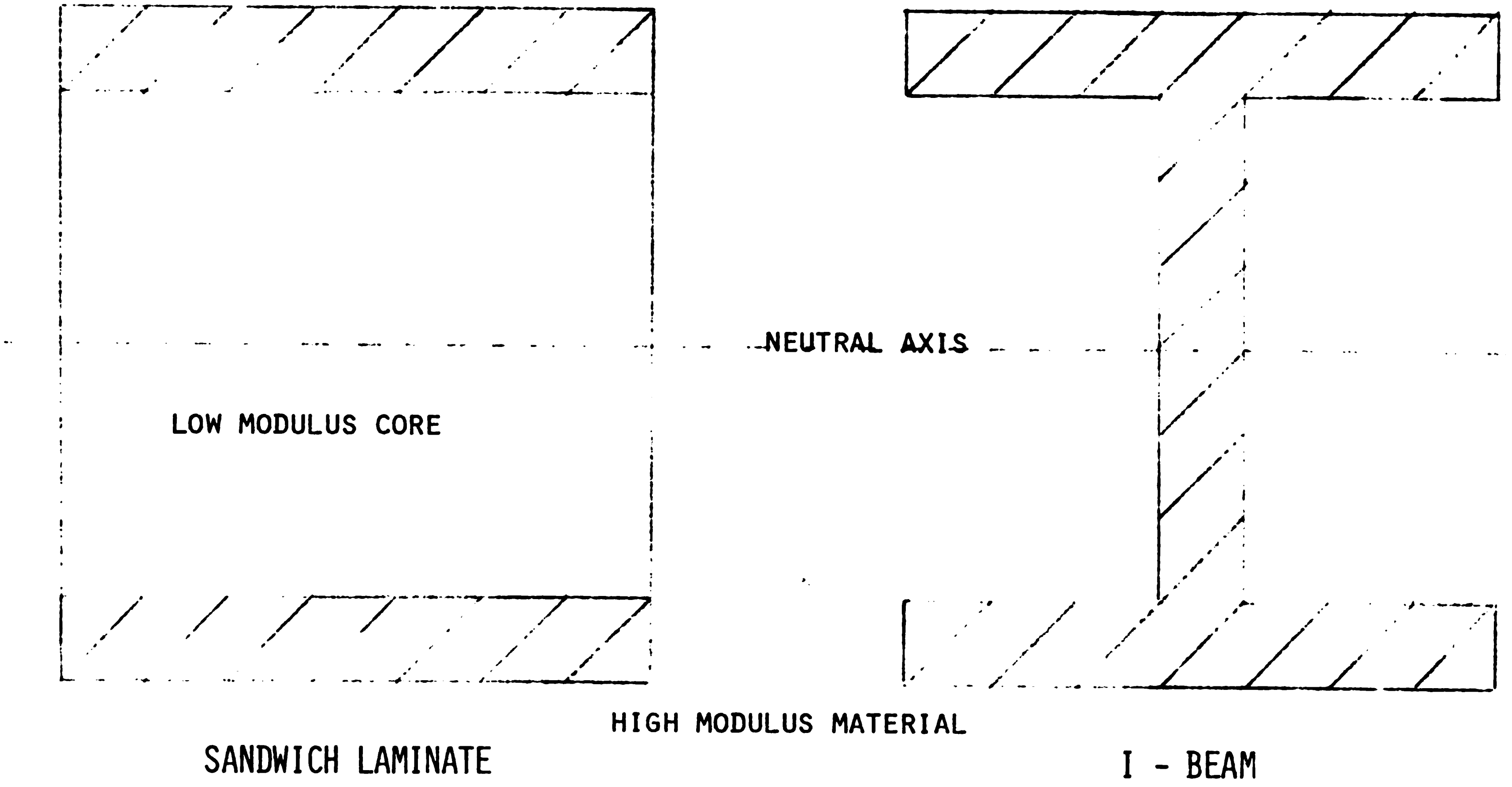

FIGURE 2-1. STRUCTURES DESIGNED FOR FLEXURAL STIFFNESS

The basic principle of using spaced facings to obtain stiff, lightweight structures was discovered by Duleau in 1820 (2-2). However, extensive practical use of this concept was not made until this century because of the lack of suitable materials, particularly the reliable adhesives that are needed to bond the facings to the core. Currently, sandwich laminates are extensively used by the aerospace and building construction and transportation industries. Due to the emphasis on site minimization in aerospace structures, balsa honeycomb or foamed plastics cored sandwiches are used in a wide variety of applications such as aircraft wings, flooring, deck levels, helicopter rotor blades, etc.

Structural building panels, consisting principally of wood, aluminum or fiberglass reinforced plastic face sheets over rigid plastic foam cores are now used extensively in schools, hospitals and office buildings because of their light weight, stiffness, sound deadening characteristics, and insulating properties. Similar panels, as well as plywood overlaid on both sides with steel or aluminum sheet have found wide use in truck and trailer doors, truck bodies, mobile homes, railroad cars, etc.

Metal-plastic sandwich laminates that are the focus of the present study differ from structural sandwiches used in the past in two aspects:

a) Thickness: The metal-plastic laminates of current interest are very thin in comparison to the usual thickness of a structural sandwich. The characteristic thickness of the laminates of interest is less than 2.5 mm (0.010 in).

b) Formability: The metal-plastic laminates of current interest can be cold formed into a complex shape by standard sheet metal forming processes. This formability derives in part from the thinness of the laminates of interest and in part because the cores consist of a solid, void free thermoplastic material. Most structural sandwiches contain rigid, hollow cores, that are too brittle to be cold formed, or would collapse in the process.

Aside from specific differences, the properties and characteristics of the metal-plastic laminates of current interest are clearly related to the broad class of structural laminates, and many of the structural and analytical techniques developed for the latter are also applicable to the metal-plastic laminates of interest.

2.2 DEVELOPERS OF A METAL-PLASTIC SANDWICH LAMINATES FOR AUTOMOTIVE APPLICATIONS

Table 2-3 is a list of the various commercial firms that were identified during the course of the program as having active

TABLE 2-3

IDENTIFIED DEVELOPERS OF METAL PLASTIC LAMINATES FOR AUTOMOTIVE APPLICATIONS

DEVELOPER	FACE SHEET	CORE	ADHESIVE	PROPERTIES DATA (NOT/AVAILABLE)
ARCO POLYMERS, INC.	Aluminum	H.D. Polyethylene	Yes	N/A
BETHLEHEM STEEL CORP.	ECS Steel	Talc Filled Polypropylene	Yes	N/A
DOW CHEMICAL USA	Steel or Aluminum	H.D. Polyethylene	Not Specified	N/A
HERCULES INC./ NATIONAL STEEL CORP.	Steel	Polypropylene Co-polymer	No	See Table 2-4
MONSANTO PLASTICS & RESIN CO.	Aluminum Alloys	Nylon 6-6	Not Specified	See Table 2-5
PHILLIPS CHEMICAL CO.	Aluminum or Steel	H.D. Polyethylene	No (uses CRO_3 metal sheet treatment)	N/A
PREFINISH METALS INC.	Steel	Polypropylene	Yes (Morprime polypropylene dispersion	N/A
SOLVAY & CIE	Steel, Aluminum Stainless Steel	Unspecified	Unspecified	
STELCO LTD.	Steel	H.D. Polyethylene Polypropylene, Other (Surlyn)	No With CRO_3 Sheet Treatment	See Table 2-6
U.S. STEEL CORP.	Steel	Polypropylene	Yes	N/A

research and development programs to support the commercialization of metal-plastic laminates for automotive applications. As can be inferred from Table 2-3, most of the developers of metal-plastic laminates have not advanced sufficiently in the technology to have obtained reproducible data of the mechanical and physical properties for the laminates they are developing, or are unwilling to release such data at the present time.

As is discussed in Appendix B, many of the key physical properties of metal-plastic sandwich laminates can be calculated quite accurately from the physical properties of the constituting materials, and from their geometrical arrangement in the laminate. The data presented in Tables 2-4 to 2-6 are in agreement with the values that would be predicted from theory from the geometry and properties of the constituting materials of each of the laminate systems considered.

2.3 HISTORICAL PERSPECTIVE

The data presented in Tables 2-4 and 2-5 were taken from two papers presented at a symposium on metal-plastic laminates that was held at the 1980 Annual Congress of the Society of Automotive Engineers. This symposium received an unusual amount of attention from the technical and business press. From the headlines of some of the news articles that issued, viz:

> "A new way to lightweighting: thin resin-core/metal sandwiches." Modern Plastics, April 1980, p. 46 (Reference 2-7).

the reader would have the impression that metal-plastic laminate technology was a brand new concept.

One cannot help but note the similarity between the above headline and the following:

> "Neuartige Verbundwerkstoffe aus Metall und Polyaethylen"
> (New Composite Materials from Metal and Polyethylene)
> Kunstoff, 59, p. 85, 1969 (Reference 2-8)

> "New Structural Laminate: Polyethylene Core, Aluminum Skins"
> Modern Plastics, 41, March 1964, p. 119 (Reference 2-9)

As evidenced by the above articles and the numerous product and process patents which have been issued, in the past two decades, (See Appendix C) the concept of structural sandwiches with thin metal skins and thermoplastic cores that can be cold formed is at least twenty years old. An extensive amount of work on polyethylene-aluminum laminates was performed in the early 1960's at the Bell Telephone Laboratories by Pohl and Spencer (2-8), and at BASF in Germany by Hoffman and co-workers (2-9). The patent literature indicates that a wide number of organizations were

TABLE 2-4

MECHANICAL PROPERTIES OF STEEL-POLYPROPYLENE COPOLYMER-STEEL SANDWICH LAMINATES

LAMINATE THICKNESS, mm	1.0	1.7	3.8	8.5
SKIN THICKNESS, mm	0.2	0.3	0.8	1.6
CORE THICKNESS, mm	0.6	1.1	2.2	5.3
CORE VOLUME RATIO, PERCENT	60	60	60	60
WEIGHT PER UNIT AREA, Kg/m^2	3.77	6.41	14.1	30.6
FLEXURAL MODULUS, GP	145	145	145	145
FLEXURAL STRENGTH, MP	325	228		
FLEXURAL FATIGUE STRENGTH, MP	138	138	152	131
TENSILE MODULUS, GP	83	83	83	83
TENSILE YIELD STRENGTH, MP	101	115	77	70
TENSILE STRENGTH, MP	163	143	143	132
PERCENT TOTAL ELONGATION PERCENT	35	37	43	47
TENSILE FATIGUE STRENGTH MP	95	97	97	97

Source: J.A. DiCello

"Steel-Polypropylene-Steel Laminate - A New Weight Reduction Material"

SAE Paper 800078, February 1980

(Reference 2-3).

TABLE 2-5

MECHANICAL PROPERTIES OF SELECTED METAL-PLASTIC LAMINATES WITH NYLON 6-6 CORES

FACE SHEET ALLOY	Aluminum 3004-H19	Aluminum 6061-T4	Steel C1005
CORE	Nylon 6-6	Nylon 6-6	Nylon 6-6
TOTAL LAMINATE THICKNESS, mm	1.60	1.53	1.00
FACE SHEET THICKNESS, mm	0.15	0.13	0.13
CORE THICKNESS, mm	1.30	1.27	0.74
CORE VOLUME RATIO, PERCENT	81.2	83.0	74.0
WEIGHT PER UNIT AREA, Kg/m^2	2.33	2.15	2.84
FLEXURAL STIFFNESS*, N/cm per cm of width	1854	1830	1860
BENDING MOMENT CAPACITY N-m per cm of width	0.168	0.240	0.343

*Flexural Stiffness = Force required to obtain a given deflection per sample width in a three point bending test with a 2.54 cm span

Source: a) L.W. McKenna, et al.
"New Light Weight Materials for Vehicle Body Panels-Aluminum/Nylon Laminates"
SAE Paper 800079, February 1980 (Reference 2-4)
b) J.C. Woodbrey, Monsanto Plastics & Resins Co.
Personal Communication, June 5, 1980 (Reference 2-5)

TABLE 2-6

MECHANICAL PROPERTIES OF SELECTED STEEL-POLYIONOMER LAMINATES

FACE SHEET	STEEL			
CORE	POLYIONOMER			
TOTAL LAMINATE THICKNESS, mm	0.69	0.78	0.94	1.03
FACE SHEET THICKNESS, mm	0.22	0.26	0.22	0.26
CORE THICKNESS, mm	0.25	0.25	0.50	0.51
CORE VOLUME RATIO, PERCENT	37.0	32.7	54.1	49.3
WEIGHT PER UNIT AREA, Kg/m^2	3.627	4.345	3.867	4.585
DEFLECTION PER UNIT LOAD PER UNIT WIDTH, cm/N PER cm WIDTH (over a 8.9 cm span)	0.0135	0.00846	0.00617	0.00576
EFFECTIVE FLEXURAL STIFFNESS, EI, KPa per cm WIDTH	253	410	570	595
APPARENT FLEXURAL MODULUS E_a^*, GPa	92	104	82	65
TENSILE MODULUS, GPA	113	131	48	110
TENSILE YIELD STRENGTH, MPA	256	195	180	143
TENSILE STRENGTH, MPA	269	222	193	168
TOTAL ELONGATION, PERCENT	17.7	32.4	19.2	32.9
YIELD POINT ELONGATION, PERCENT	2.2	1.5	3.7	1.3

SOURCE OF DATA:

S. Rocys
"Steel-Plastic-Steel Composite Sheet, Experimental-Exploratory"
Sales Engineering Internal Report, Stelco Inc., Hamilton, Ontario, Can.
January 1980 (Reference 2-6)

interested in laminates over the years, including among others, Union Carbide Corporation, Esso Research and Engineering Company, Phillips Petroleum Company, Stelco Ltd., Imperial Chemical Industries, Ltd., Dow Chemical Company, Mitsui Petrochemical Industries, Ltd., etc.

In spite of this extensive patent activity, metal-plastic laminates have been commercialized by only two firms. In 1969, Alusuisse (Swiss Aluminum Corp.) introduced in Europe an aluminum-polyethylene-aluminum laminate uder the trade name of Alucobond.^{R} This material was introduced in the U.S. in 1978 by Consolidated Aluminum Corporation, an Alusuisse subsidiary. Typical properties of Alucobond^R are given in Table 2-7. It is available only as a fairly thick laminate (3mm to 8mm), and has been principally used for architectural and interior design purposes where its extreme flatness and its availability in a wide range of colors and reflective finishes, make it an eye-catching material. Alucobond^R has also been used for the body panels and floor of an electric car manufactured by Marathon Electric Vehicle Co., Inc. of Montreal, Canada, as will be discussed in more detail in Section 6.1. It should be noted that Alucobond^R is currently being manufactured in the U.S. (at a plant in Benton, KY) as well as in Europe.

Mitsui Petrochemical Industries, Ltd. introduced a competitive material to Alucobond^R in Japan in 1975 under the Planium^R trade name. Typical properties of these laminates are summarized in Table 2-8. Planium^R differs from Alucobond^R in that it uses high density polyethylene instead of low density polyethylene for the core, and in the adhesive system used to bond the polymer to the face sheets. From issued patents, it is inferred that an ethylene-acrylic acid-tert-butyl acrylate co-polymer is the adhesive for Alucobond^R, where as a polyethylene-sorbene 2, 3 dicarboxylic anhydride co-polymer or an ethylene 1, 2, 3, 6 tetrahydrophthalic Acid co-polymer is the adhesive used to bond Planium^R. Planium^R has been principally used in Japan for architectural purposes, with a major application being the walls of modular bathrooms for prefabricated housing. Planium^R has not been used in automotive applications. Mitsui & Co. (USA), Inc. is trying to introduce Planium^R in the U.S. at the moment.

TABLE 2-7

TYPICAL MECHANICAL PROPERTIES OF ALUCOBOND^R

FACE SHEET MATERIAL: 3003-H22 or 5000-H22 Aluminum Alloys

FACE SHEET THICKNESS: 0.5 mm (0.020 in)

CORE: Low Density Polyethylene with 8 percent carbon black filler

LAMINATE THICKNESS				
mm	3.0	4.0	6.0	8.0
(in)	1/8	5/32	1/4	5/16
WEIGHT PER UNIT AREA				
KG /m^2	4.50	5.48	7.29	9.10
(lb/ft^2)	(0.92)	(1.12)	(1.49)	(1.86)
YIELD STRENGTH				
MPA	38	31	22	16
(Psi)	(5500)	(4500)	(3200)	(2300)
ULTIMATE STRENGTH				
MPA	48	41	31	24
(Psi)	(7000)	(6000)	(4500)	(3500)
ELONGATION, PERCENT	12-24	12-24	12-24	12-24
TENSILE MODULUS				
GPA	23	18	12	9
(10^6 psi)	(3.4)	(2.6)	(1.7)	(1.3)
FLEXURAL MODULUS				
10 cm (4 in) SPAN				
GPA	31	19	13	8
(10^6 psi)	(4.5)	(2.7)	(1.9)	(1.2)
20 cm (8 in) SPAN				
GPA	40	30	22	15
(10^6 psi)	(5.8)	(4.4)	(3.2)	(2.2)
IZOD IMPACT STRENGTH				
J	0.6	1.0	1.3	1.6
(ft/lbs)	(1.0)	(1.5)	(2.0)	(2.5)
TEMPERATURE EXPOSURE RANGE,				
°C	-48 to +80			
°F	(-55 to +175)			

SOURCE: Consolidated Aluminum Corp.
Brochure AD 540
Reference 2-10

TABLE 2 - 8

TYPICAL PHYSICAL PROPERTIES OF PLANIUM^{TM} HIGH DENSITY POLYETHYLENE-ALUMINUM LAMINATES

Nomenclature Item	Unit	Testing Method (ASTM)	PLANIUM			
			#2100	#2200	#3200	#4200
Total thickness	mm		2	2	3	4
Face sheet thickness	mm		0.1	0.2	0.2	0.2
Weight	kg/m^2		2.25	2.60	3.54	4.50
Tensile strength	kg/m^2	D638	314	427	342	306
Elongation	%	D368	9	8	9	11
Flexural stiffness	kg·cm^2/cm	C393	133	233	565	1,067
Modulus of elasticity in bending	kg/cm^2	C393	2.0×10^5	3.5×10^5	2.5×10^5	2.0×10^5
Peel strength	kg/in.	D903	10	14	15	16
Deflection temp.	°C	D648	132	134	134	132
Linear thermal expansion coefficient	mm/mm/°C		3.5×10^{-6}	29.2×10^{-6}	32.2×10^{-6}	35.0×10^{-6}
Heat conductance	Kcal/m·hr·°C		0.334	0.379	0.350	0.334
Thermal resistance (Perpendicular wall surface)	m^2·hr·°C/Kcal		0.490	0.489	0.493	0.496
Sound insulation 500 c/s	dB	ISO R140	15	17	19	22
1,000 c/s	dB	ISO R140	20	21	23	26
Minimum bend radius of curvature (Typical value for unembossed)						
Crosswise	mm		8	10	13	16
Lengthwise	mm		19	22	27	34

Source: MITSUI PETROCHEMICAL INDUSTRIES, LTD., Tokyo, Japan, Reference 2-11

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3.0 WEIGHT REDUCTION POTENTIAL OF METAL-PLASTIC LAMINATES

3.1 INTRODUCTION

Functional requirements demand that vehicle components meet static and dynamic load design criteria. Static load design criteria control the rigidity and/or strength of a specific component member or of the entire vehicle structure. The dynamic load design criteria requires that the entire vehicle and specific component members support the transient loads which a moving vehicle can be exposed to. Since a vehicle can be expected to be on the road for ten or more years, materials have to be sufficiently durable to meet these criteria over this period of time. Furthermore, besides the above criteria, there are crashworthiness load design criteria which are derived from requirements for occupant safety during vehicular impact.

These various criteria all have to be met when a design change involving a new component geometry or an alternate material of construction is being considered. A simplified approach to this complex problem was developed by Chang and Justusson (3-1), who assumed that materials substitution would be made on a functional basis, and that the component made with an alternate material would meet or exceed the structural characteristics of the baseline structure being replaced. In most cases, the material of construction of the baseline structure is mild steel.

The analysis focuses on the replacement of a baseline structure with an "equivalent" structure made from a different material that has the same major dimensions, geometrical design characteristics and function, except for thickness which can be adjusted to meet structural performance requirements such as stiffness, strength, fatigue strength, denting resistance, buckling resistance and vibration response. The method further assumes that the various components can be classified according to their geometry into either flat plates or solid sections, panels or thin-walled structures. Panel members (e.g. hood roof panel, door panel, deck lid) and thin-wall beam members (e.g. chassis frame, pillars and rocker panels) account for most of the vehicle weight. Solid section members (e.g. various reinforcement brackets, hinges, hood latch supports, flat decking) contribute comparatively less to the total weight of the vehicle.

By considering similar geometrics for equivalent structures, the functional relationship between the structural criteria and the corresponding design variables can be simplified by eliminating many complicated geometric factors. Hence, design parameters can be reduced to a function of basic material properties: modules of eleasticity (E), Poisson's ratio (ν), yield strength (σy), by density (ρ) and thickness (t). Equations involving these parameters are given in Tables 3-1 to 3-3 for the various geometries considered.

TABLE 3-1 COMPARISON OF REQUIRED STRUCTURAL CHARACTERISTICS FOR PANEL MEMBERS -- DIRECT SUBSTITUTION OF MATERIAL --

Structural Characteristic	Ratio of Structural Characteristics*	Thickness Ratio Required for Equal Structural Characteristics
Stiffness, S (Oil Canning Resistance)	$\frac{S_n}{S_o} = \frac{E_n}{E_o}\left(\frac{t_n}{t_o}\right)^2$	$\frac{t_n}{t_o} = \left(\frac{E_o}{E_n}\right)^{\frac{1}{2}}$
Denting Resistance, D	$\frac{D_n}{D_o} = \left(\frac{\sigma_{yn}(\dot{\epsilon})t_n^2}{\sigma_{yo}(\dot{\epsilon})t_o^2}\right)^2 \frac{S_o}{S_n}$	$\frac{t_n}{t_o} = \frac{\sigma_{yo}(\dot{\epsilon})}{\sigma_{yn}(\dot{\epsilon})}\left(\frac{E_n}{E_o}\right)^{\frac{1}{2}}$
Buckling Resistance, B	$\frac{B_n}{B_o} = \frac{E_n}{E_o}\frac{1-\nu_o^2}{1-\nu_n^2}\left(\frac{t_n}{t_o}\right)^3$	$\frac{t_n}{t_o} = \left(\frac{1-\nu_o^2}{1-\nu_n^2}\frac{E_o}{E_n}\right)^{\frac{1}{3}}$
Stress Yield Factor, Y	$\frac{Y_n}{Y_o} = \frac{\sigma_{yn}(\dot{\epsilon})}{\sigma_{yo}(\dot{\epsilon})}\frac{E_o}{E_n}\frac{\bar{S}_n}{\bar{S}_o}$	$\frac{\bar{S}_n}{\bar{S}_o} = \frac{E_n}{E_o}\frac{\sigma_{yo}(\dot{\epsilon})}{\sigma_{yn}(\dot{\epsilon})}$
Vibration Frequency, F	$\frac{F_n}{F_o} = \left(\frac{E_n}{E_o}\frac{t_n}{t_o}\frac{\rho_o}{\rho_n}\right)^{\frac{1}{2}}$	$\frac{t_n}{t_o} = \frac{E_o}{E_n}\frac{\rho_n}{\rho_o}$

*Subscripts n and o refer to new material and original material.

SOURCE: Reference 3-1

TABLE 3-2 COMPARISON OF REQUIRED STRUCTURAL CHARACTERISTICS FOR THIN-WALLED BEAM MEMBERS --DIRECT SUBSTITUTION OF MATERIALS--

Structural Characteristic	Ratio of Structural Characteristics*	Thickness Ratio Required for Equal Structural Characteristics
Bending Stiffness, S^b	$\frac{S^b_n}{S^b_o} = \frac{E_n}{E_o}\frac{t_n}{t_o}$	$\frac{t_n}{t_o} = \frac{E_o}{E_n}$
Torsional Stiffness, S^t	$\frac{S^t_n}{S^t_o} = \frac{G_n}{G_o}\frac{t_n}{t_o}$ (closed section)	$\frac{t_n}{t_o} = \frac{G_o}{G_n}$
	$= \frac{E_n}{E_o}\frac{t_n}{t_o}$ (open section)	$\frac{t_n}{t_o} = \frac{E_o}{E_n}$
Buckling Resistance, B	$\frac{B_n}{B_o} = \frac{E_n}{E_o}\frac{t_n}{t_o}$	$\frac{t_n}{t_o} = \frac{E_n}{E_o}$
Local Buckling Resistance, L	$\frac{L_n}{L_o} = \frac{E_n}{E_o}\frac{1-\nu_o^2}{1-\nu_n^2}\left(\frac{t_n}{t_o}\right)^2$	$\frac{t_n}{t_o} = \left(\frac{1-\nu_n^2}{1-\nu_o^2}\frac{E_o}{E_n}\right)^{\frac{1}{2}}$
Crippling Resistance, C	$\frac{C_n}{C_o} = \left(\frac{E_n}{E_o}\frac{\sigma_{yn}}{\sigma_{yo}}\right)^{\frac{1}{2}}\left(\frac{t_n}{t_o}\right)^{1.75}$	$\frac{t_n}{t_o} = \left(\frac{E_o}{E_n}\frac{\sigma_{yo}}{\sigma_{yn}}\right)^{\frac{1}{3.5}}$
Stress Yield Factor, Y	$\frac{Y_n}{Y_o} = \frac{\sigma_{yn}(\dot{\varepsilon})}{\sigma_{yo}(\dot{\varepsilon})}\frac{E_o}{E_n}\frac{S_n}{S_o}$	$\frac{S_n}{S_o} = \frac{E_n}{E_o}\frac{\sigma_{yo}(\dot{\varepsilon})}{\sigma_{yn}(\dot{\varepsilon})}$
Vibration Frequency, F	$\frac{F_n}{F_o} = \left(\frac{E_n}{E_n}\frac{\rho_o}{\rho_n}\right)^{\frac{1}{2}}$	—

*Subscripts n and o refer to new material and original material.

SOURCE: Reference 3-1

TABLE 3-3 COMPARISON OF REQUIRED STRUCTURAL CHARACTERISTICS FOR SOLID SECTIONS
--DIRECT SUBSTITUTION OF MATERIAL--

STRUCTURAL CHARACTERISTICS	RATIO OF STRUCTURAL CHARACTERISTICS*	THICKNESS RATIO REQUIRED FOR EQUAL STRUCTURAL CHARACTERISTICS
Equal Bending Stiffness	$\frac{Sn}{So} = \frac{En}{Eo} \left(\frac{tn}{to}\right)^3$	$\frac{tn}{to} = \left(\frac{Eo}{En}\right)^{1/3}$
Equal Bending Moment Resistance	$\frac{Mn}{Mo} = \frac{\sigma n}{\sigma o} \left(\frac{tn}{to}\right)^2$	$\frac{tn}{to} = \left(\frac{\sigma o}{\sigma n}\right)^{1/2}$
Equal Bending Moment Resistance in Fatigue	$\frac{M^F n}{M^F o} = \frac{\sigma n^F}{\sigma o^F} \left(\frac{tn}{to}\right)^2$	$\frac{tn}{to} = \left(\frac{\sigma o^F}{\sigma n^F}\right)^{1/2}$

* Subscripts n and o refer to new material and original material

SOURCE: Reference 3-2

The method of analysis does not consider any design change other than adjusting thickness, even though such design changes would occur to arrive at an optimum modified design. The analysis, furthermore, does not take into account other considerations such as ease of fabrication, cost, durability, etc.

3.2 SUBSTITUTION OF STEEL BY METAL-PLASTIC SANDWICH LAMINATES

The stiffness to weight ratio of a metal-plastic sandwich laminate is its most attractive property when considering the replacement of steel with a laminate to achieve weight reductions. A laminate will be a weight effective substitute for steel in those components where flexural stiffness is the design constraining property. At the same time, laminates should not be considered for components where the structural material is subjected to significant in-plane stresses since, in these instances, no weight savings result.

If one neglects any shear induced deflections due to the low modulus of the core, the relative thickness of a metal-plastic sandwich laminate sheet to the thickness of a steel sheet of equivalent flexural stiffness, will vary as a function of the modulus of the metal facings, E_f, the core volume ratio, α, (which is the ratio of the thickness of the plastic core to the total thickness of the laminate), and the geometry of the component.

The relative thickness of a steel or aluminum faced laminate to a steel sheet of equivalent flexural stiffness is presented as a function of core volume ratio for a flat plate and for a curved panel in Figure 3-1. In case of the flat plate, the stiffness is a function of the effective modulus times the thickness cubed, whereas for the panels, the stiffness is a function of the effective modulus times approximately the thickness squared.

The relative thickness of a laminate to a steel sheet of equivalent stiffness increases as the core volume ratio increases since the effective modulus of the laminate decreases. For steel faced laminates, the increase in thickness required to maintain constant stiffness is relatively modest for values of the core volume ratio of less than 0.7. The geometry of the system has little impact on the required thickness as well.

For example, the required increase in thickness over steel for a steel faced laminate with a core volume ratio of 0.6 would only be 8.4 percent in case of a flat plate and 1.4 percent for a curved panel.

An aluminum faced laminate would be significantly thicker than an equivalent steel sheet because of the relatively low modulus of the aluminum facings relative to that of steel, which in turn, results in a laminate that has a relatively low effective modulus. As a result, the relative thickness required to

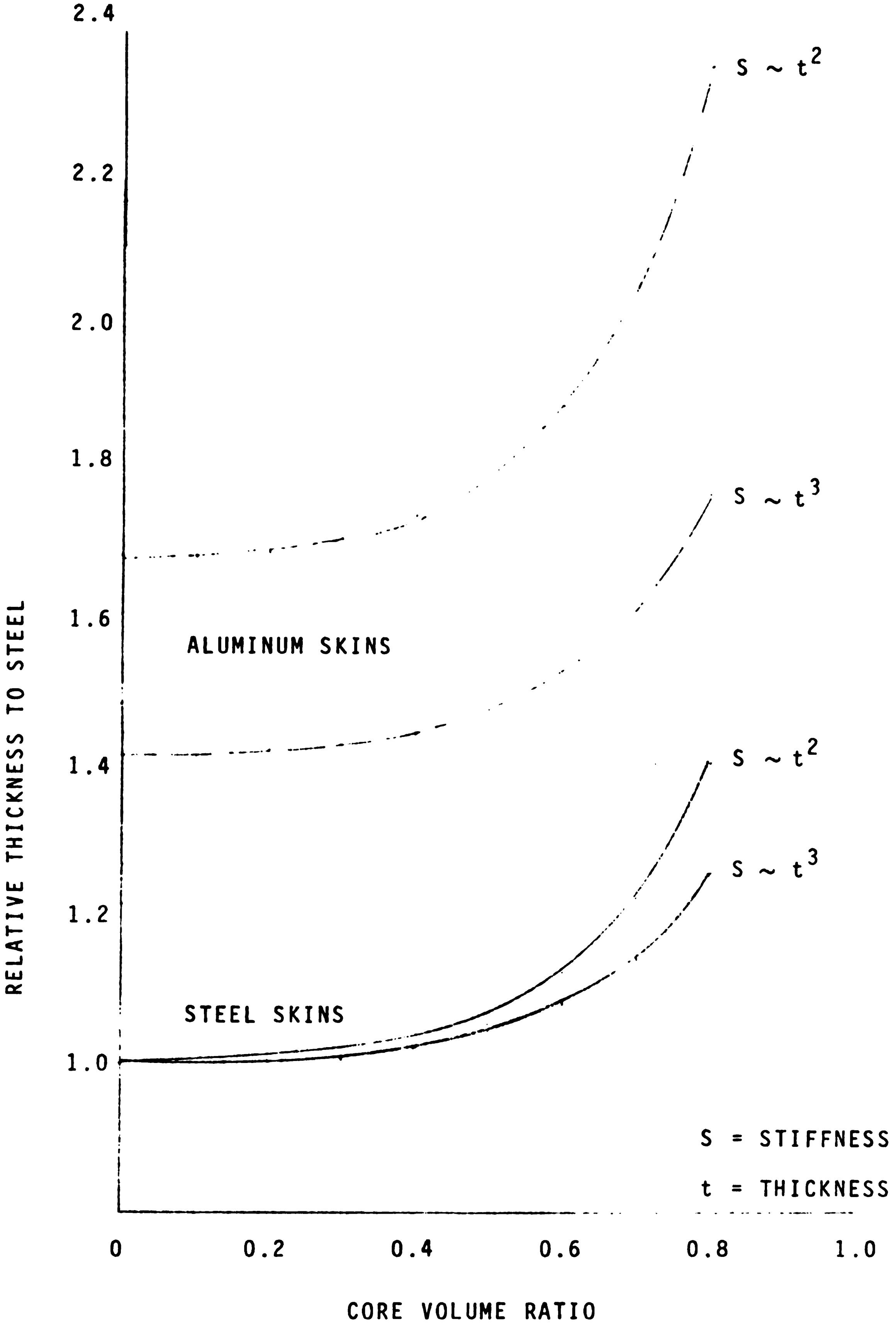


FIGURE 3-1. RELATIVE THICKNESS OF LAMINATES OF STIFFNESS EQUAL TO STEEL

maintain constant stiffness is also a strong function of system geometry. The required increase in thickness over steel for an aluminum faced laminate with a core volume ratio of 0.6, would be 53.2 percent for a flat plate and 89.7 percent for a curved panel, as shown in Figure 3-2.

3.3 WEIGHT REDUCTION POTENTIAL OF STEEL FACED LAMINATES

The relative weight of a steel-polypropylene laminate functionally equivalent to a steel sheet is given in Figure 3-2 on the basis of the results presented in Figure 3-1, assuming that the weight ratio per unit area of a laminate and steel is given by the following equation:

$$\frac{W_L}{W_S} + \frac{t_L}{t_S} \quad \frac{\rho_f \ (1-\alpha) \ + \alpha \rho_c}{S} \qquad (3\text{-}1)$$

Where

W_L = Weight of laminate per unit area

W_S = Weight of steel per unit area

t_L = thickness of laminate

t_S = thickness of steel

α = core volume ratio

ρ_c = density of the laminate polymer core

ρ_f = density of the laminate metal facings

ρ_s = density of steel

Figure 3-2 presents the relative weight of a steel faced (ρ_f = 7.84 gr/cm^3), polypropylene core (ρ_c = 0.91 gr/cm^3) laminate to sheet steel (ρ_s = 7.84 gr/cm^3) of equivalent stiffness as a function of core volume ratio for a flat plate and a curved panel. In both instances, the relative weight decreases rapidly as a function of α, the core volume ratio, until a minimum is reached, and then, the relative weight increases for further increases in the value of $\alpha > 0.96$, whereas for a curved panel the minimum weight ratio is 0.378 at a value of $\alpha = 0.91$.

These minimum weight values are not practially achievable because they require unusually thin facings which are not necessarily available, and because the design results in the very thin faces having to carry very high stresses under modest moments.

The ratio of the thickness of laminate facing to the thickness of steel required as a function of α to maintain equivalent

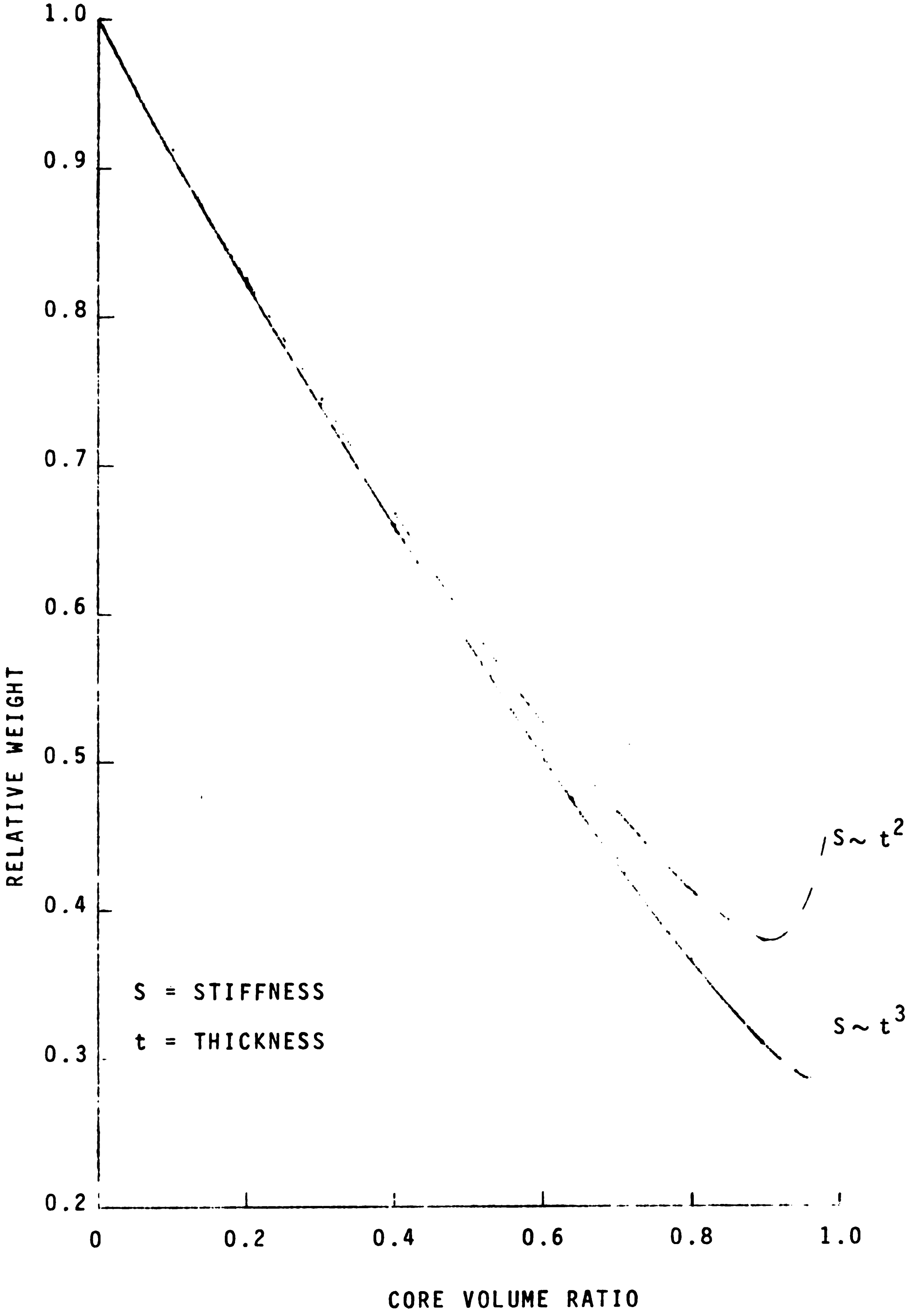


FIGURE 3-2 RELATIVE WEIGHT OF STEEL-POLYPROPYLENE SANDWICH LAMINATE TO STEEL SHEET OF EQUAL STIFFNESS

stiffness is presented in Figure 3-3 for both steel end aluminum faced laminates. Currently, the minimum thickness of the steel sheet commonly used in panel applications is 0.80 mm. In the future, steel sheets as thin as 0.70 mm could be used, however. The minimum thickness of steel sheet currently produced for the packaging industry is 0.15 mm. However, this material is not fully annealed and is not comparable in drawing qualities to standard automotive sheet steel. The minimum commercial thickness fully annealed, aluminum killed sheet steel is currently 0.18 mm to 0.20 mm. If one wishes to replace 0.80 mm steel sheet with a steel faced laminate, the minimum value of the thickness ratio of laminate facing to steel is 0.19 for a laminate with partially annealed facings and 0.23 for a laminate with fully annealed facings. The corresponding values of the core volume ratio are approximately 0.66 to 0.68 for the lower value and about 0.59 to 0.61 for the upper value, depending on the assumed geometry.

The developers of steel faced laminates such as National Steel Corp. are focusing on laminates that have a core volume ratio of approximately 60 percent. For thinner laminates, this value of relative core thickness is dictated by the minimum available thickness of formable steel for the facings. In this case, with a polypropylene core that has a density of 0.91 gr/cm^3, the relative weight of laminate functionally equivalent to steel is approximately 50 percent that of steel.

As one considers the replacement of thinner steel sheet, one is constrained by the minimum thickness of steel available for the facings, the weight savings that could be attained with laminates decreases. If the minimum thickness for fully annealed steel remains 0.18 mm, reducing the thickness of the steel to be replaced to 0.70 mm, results in a ratio of $t_f/t_s = 0.26$, and a corresponding value of α of about 0.50. At this core volume ratio, the relative weight of a steel faced laminate to steel would now be 60 percent of that of steel, resulting in a weight savings of only 40 percent.

Conversely, as the thickness of the steel sheet being considered for substitution increases, smaller values of t_f/t_s are attainable so that one can construct a laminate that has a greater core volume ratio, and a lower weight per unit area relative to steel. Constraints which govern in this case now become the specified bending moment capacity or the maximum laminate thickness. Schwartz and Rosato (3-3) have shown that the core weight for a minimum weight sandwich of specified bending moment capacity (and for which the strength of the facings is independent of thickness) is equal to half the weight of the sandwich minus the bond weight. For a steel faced sandwich with a self-adhering polypropylene core with a density of 0.91 gr/cm^3, this correspondence to a core volume ratio of 0.89. This value is somewhat smaller than that of the core volume ratio that results in a stiffness based minimum weight laminate.

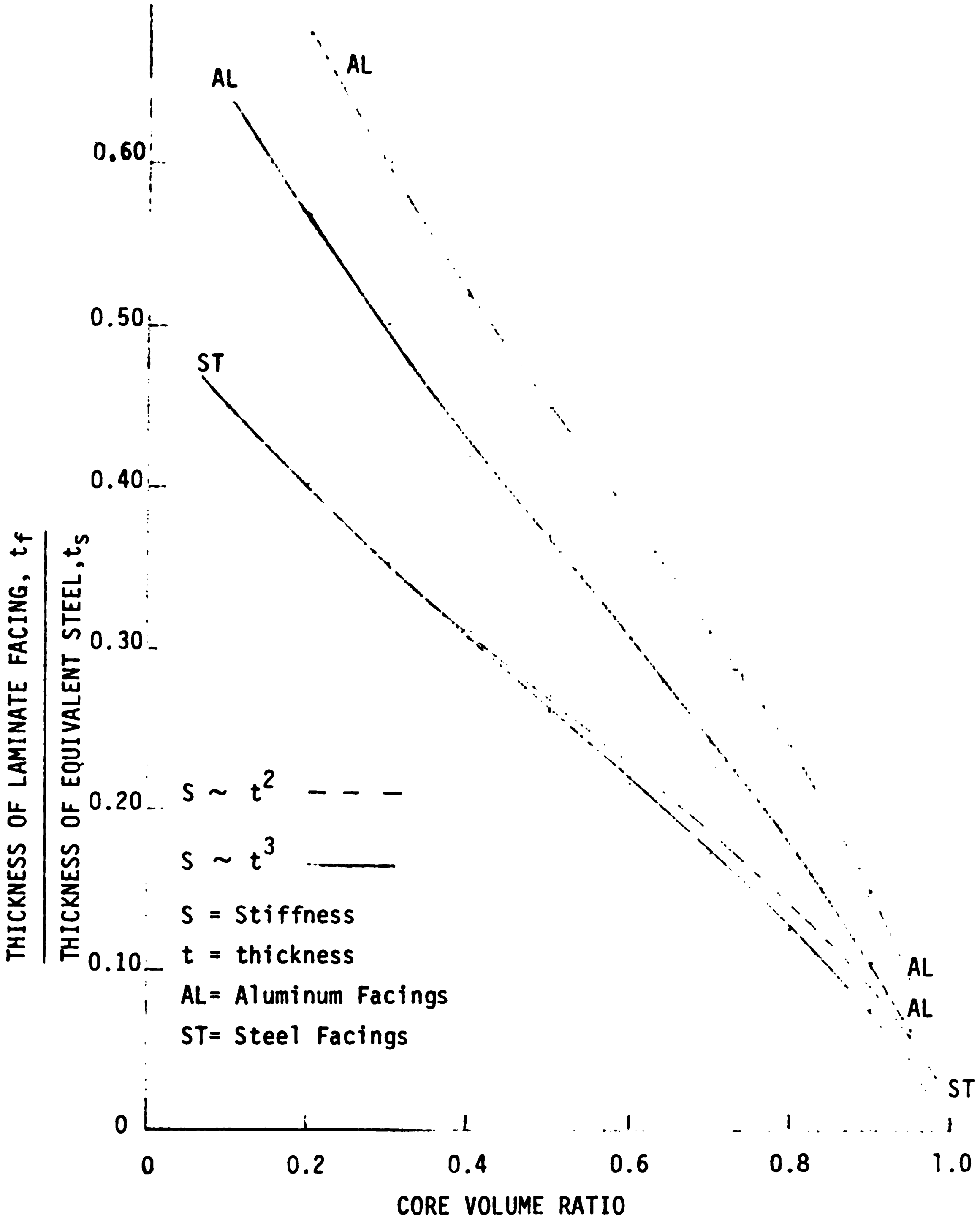


FIGURE 3-3. RATIO OF METAL FACING THICKNESS TO THICKNESS OF STEEL SHEET OF EQUIVALENT STIFFNESS AS A FUNCTION OF LAMINATE CORE VOLUME RATIO.

A more severe limitation on the core volume ratio, and the weight reduction potential of steel faced laminates replacing thicker steel sheets, is the rapid increase in laminate thickness required to achieve equivalent stiffness for values of $\alpha > 0.6$ as shown in Figure 3-1. The laminates which results in a minimum weight ratio in Figure 3-2 would have to be approximately 92 percent thicker than the steel sheet being replaced, which may not be feasible. A second consideration is that a thinner laminate with thicker face sheets will have better forming characteristics than a thick laminate with thin face sheets, as will be discussed in Section 5-2.

The density of the polymer core has a slight effect on the relative weight of a steel faced laminate to that of a steel sheet of equivalent thickness as shown in Figure 3-4. The proportional effect of the polymer core density increases as the core volume ratio increases, as one would expect. At a value of the core volume ratio of 0.60, a 50 percent increase in core density results in a relative increase in laminate weight of less than 10 percent. This is because the density of steel (7.86 gr/cm^3) is so much higher than that of any of the polymers being considered as candidate laminate cores.

3.4 WEIGHT REDUCTION POTENTIAL OF ALUMINUM FACED LAMINATES

The relative weight of an aluminum-nylong sandwich laminate to that of a steel sheet of equivalent thickness as a function of the core volume ratio is presented in Figure 3-5. Comparing this figure to Figure 3-2, which presents comparable data for steel faced laminates, one notices that the relative weight of aluminum faced laminates is much less sensitive to the core volume ratio than steel faced laminates, but much more sensitive to the geometry assumed. For a flat plate configuration $(s \sim t^3)$, the minimum laminate weight ratio is about 0.332 which is attained at a core volume ratio of 0.76 while for a curved panel $(s \sim t^2)$, the minimum laminate weight ratio is about 0.42 which is attained at a core volume ratio of 0.63. These calculated minimum weight ratios are higher than those calculated for steel faced laminates, and are attained at lower values of the core volume ratio.

As shown in Figure 3-5 for a flat plate configuration, an aluminum faced laminate with a value of = 0.76, has a value of $t_f/t_s = 0.21$. For a curved panel configuration, an aluminum faced laminate with a value of $\alpha = 0.63$ requires a value of $t_f/t_s = 0.34$.

Non-heat-treatable aluminum alloys such as 1100, 3003, 5052, are currently commercially available as coiled sheets in gauges as thin as 0.15 mm. Heat treatable aluminum alloys such as 2014, 6061 or 7075, of the same thicknesses, are available from some suppliers. However the minimum thickness which these alloys are available commercially in heated, treated tempers is 0.22 mm. In considering the replacement of 0.8 mm steel sheet by aluminum faced laminates, the minimum value of $t_f/t_s = 0.19$ except for

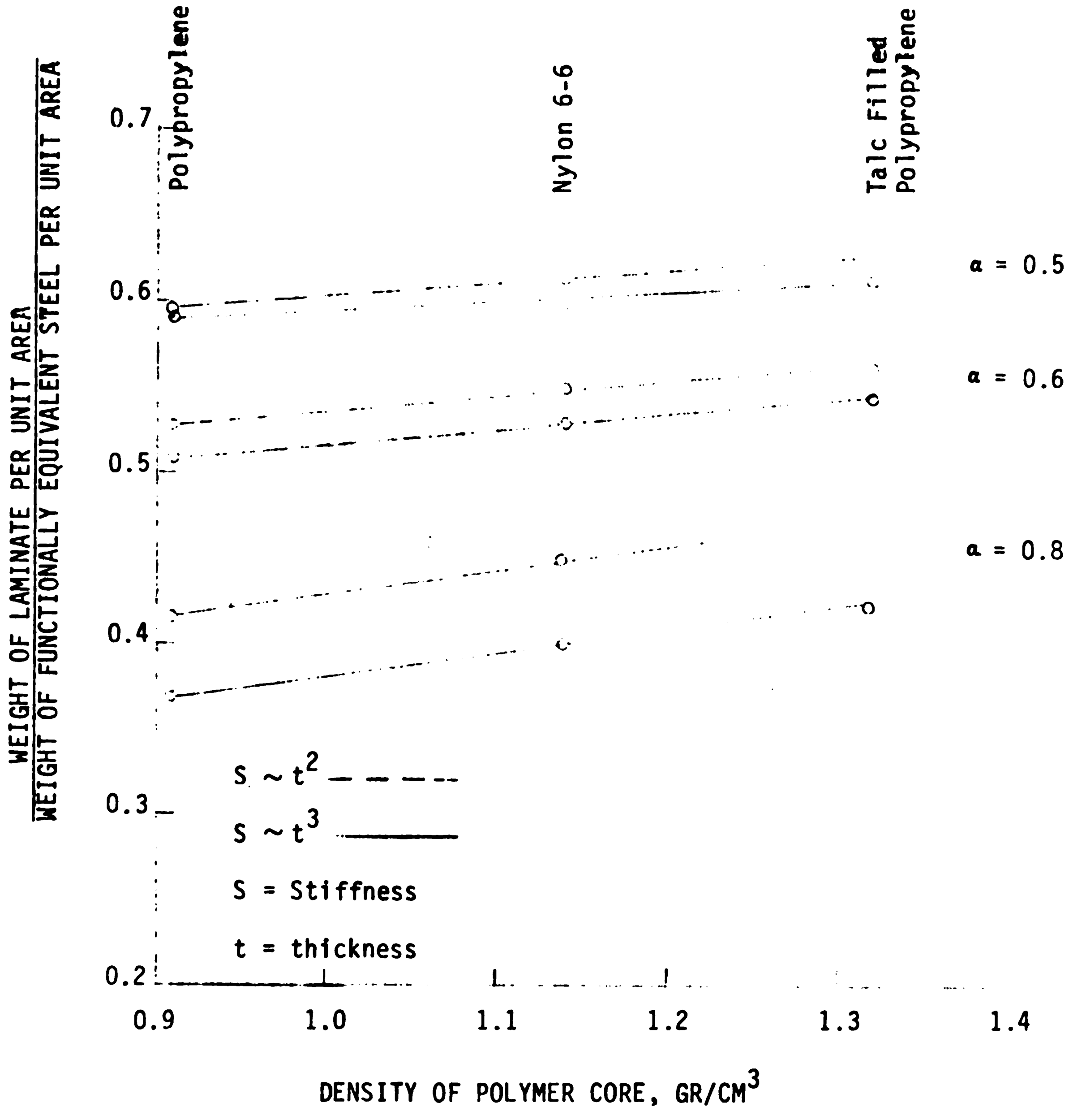


FIGURE 3-4. EFFECT OF THE DENSITY OF THE POLYMER CORE ON THE RELATIVE WEIGHT OF A STEEL FACED SANDWICH LAMINATE AND OF A STEEL SHEET OF EQUIVALENT STIFFNESS FOR VARIOUS CORE VOLUME RATIOS (α).

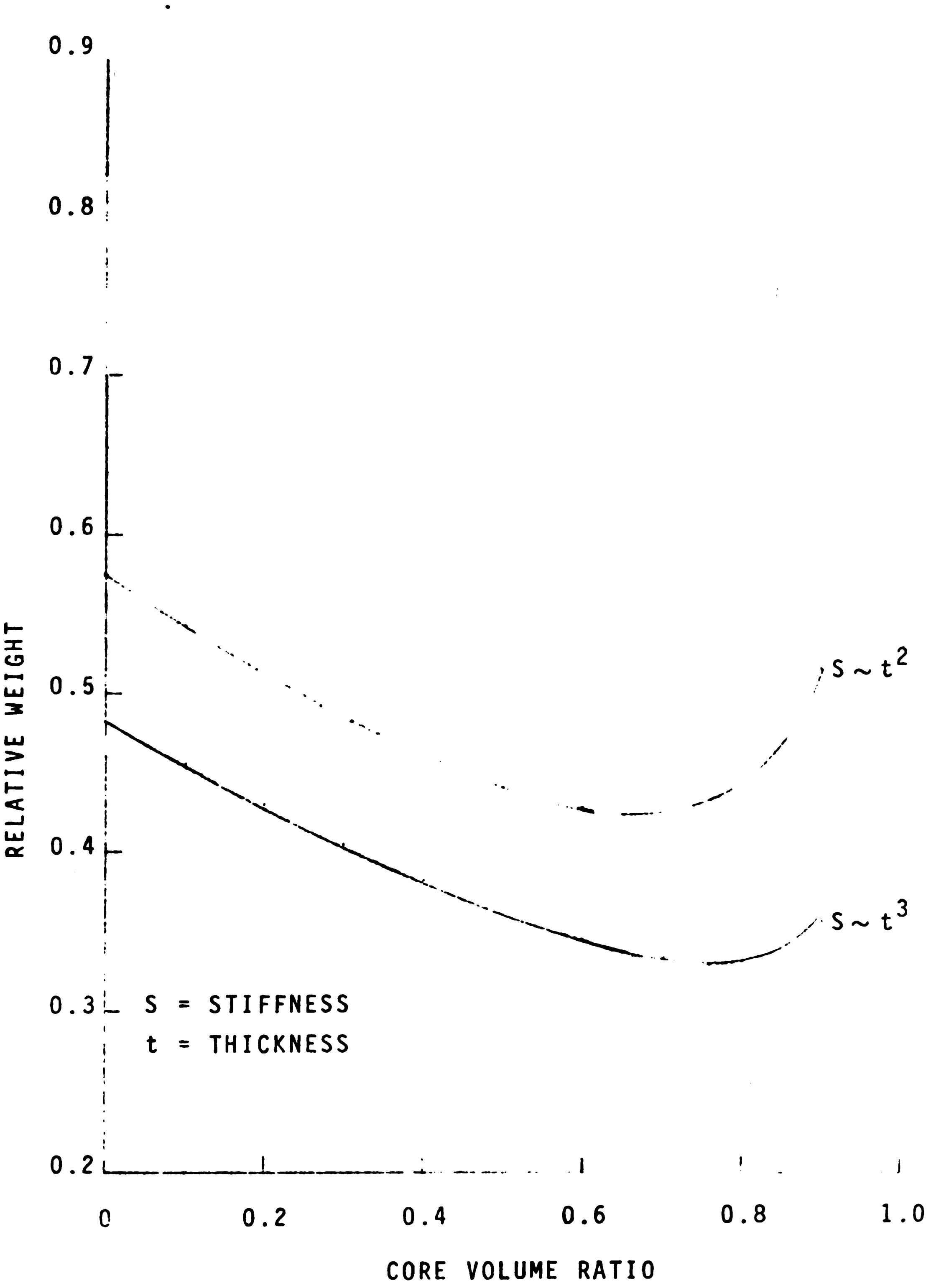


FIGURE 3-5 RELATIVE WEIGHT OF ALUMINUM-NYLON SANDWICH LAMINATE TO STEEL SHEET OF EQUIVALENT STIFFNESS

heat treated tempers where the minimum value of this ratio is 0.28. The minimum value of t_f/t_s that can be achieved with non-heat-treatable alloys is smaller than required to achieve the minimum weight laminates for either a flat plate or curved panel configuration. The minimum value of t_f/t_s that can be attained with heat treated tempers is sufficient for the minimum weight laminate for a panel configuration, but not for a flat plate. The value of $\alpha = 0.64$ corresponds to $t_f/t_s = 0.28$ for a flat configuration. At this value of α, the weight ratio of the laminate to a steel place of equivalent stiffnesss is 0.34 which is only marginally higher (1 percent) than the optimum values.

The optimum value α for minimum weight aluminum faced nylon laminate specified bending moment is 0.704 according to Schwartz and Rosato's analysis. This value of α, is less than the value of α that results in a minimum weight laminate of equivalent stiffness for a flat plate, but larger than this minimum weight value for a curved panel. For a flat plate model, at $\alpha = 0.704$, the weight ratio of a nylon-aluminum laminate to a steel plate of equivalent stiffness is 0.335, a fraction of a percent higher than the minimum weight value 0.332 at $\alpha = 0.76$.

Referring to Figure 3-1, aluminum faced laminates of minimum weight will be 60 percent to 70 percent thicker than a flat steel plate of equivalent stiffness, and approximately twice as thick as a curved panel of equivalent thickness. A significant increase in thickness is a general constraint against the substitution of aluminum faced laminates for steel because of the low modulus of facings.

The effect of the density of the polymer core on the weight ratio of aluminum faced laminates to a steel sheet of equivalent stiffness is presented in Figure 3-6. This relatively small effect of core volume ratio on weight savings indicated in Figure 3-5 is reflected by the grouping of the lines in Figure 3-6. Increasing the density of the core has a proportionately greater effect on the weight savings of aluminum faced laminates than for steel faced laminates (as shown in Figure 3-4) because the density of aluminum is much less than that of steel. The effect of core density on the weight increases with α, and is greater for a flat plate than a panel.

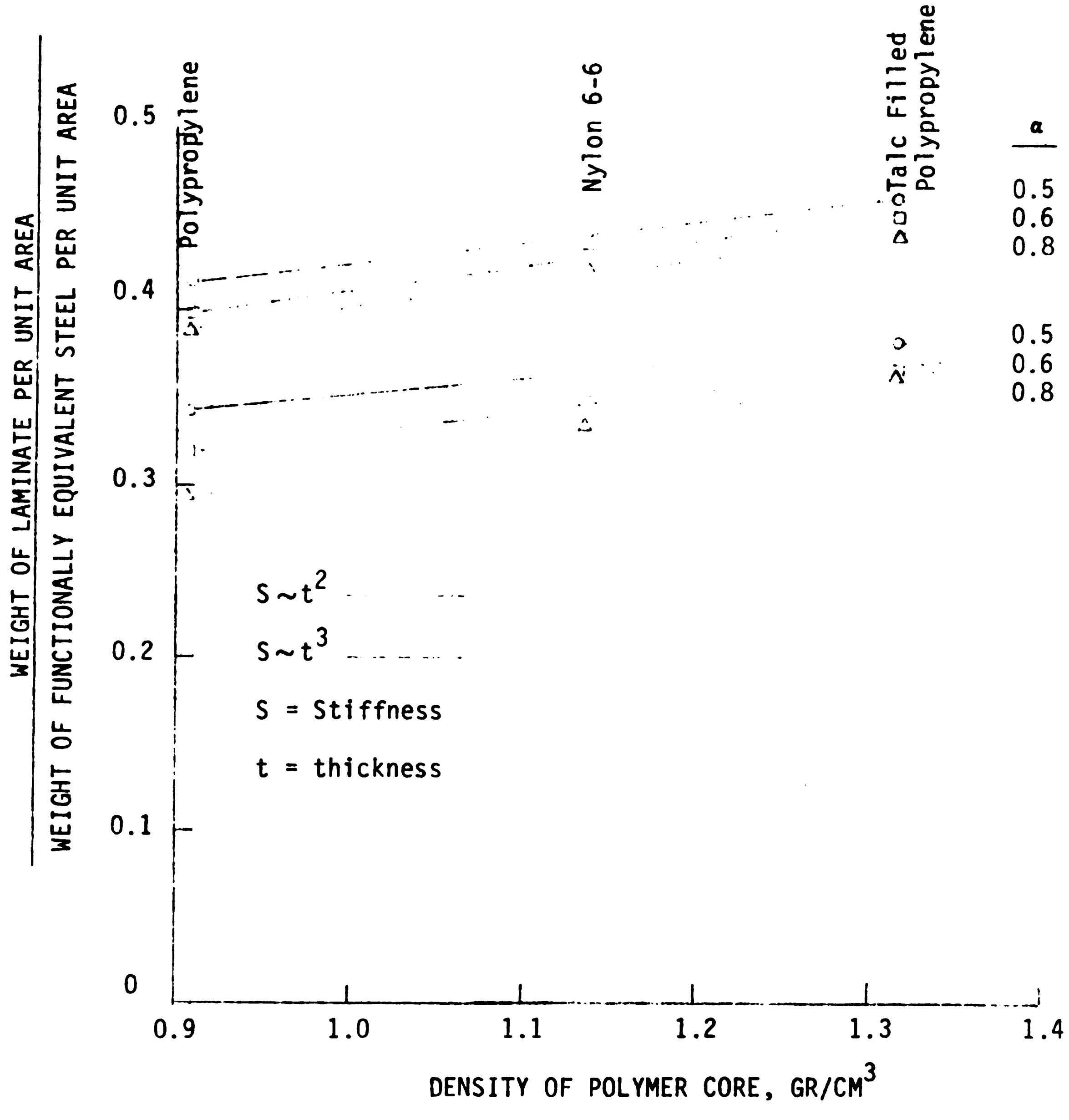


FIGURE 3-6. EFFECT OF THE DENSITY OF THE POLYMER CORE ON THE RELATIVE WEIGHT OF AN ALUMINUM FACED SANDWICH LAMINATE AND OF A STEEL SHEET OF EQUIVALENT STIFFNESS FOR VARIOUS CORE VOLUME RATIOS (a).

CHAPTER 3 REFERENCES

3-1 D. C. Chang and T. W. Justusson, "Structural Requirement in Materials Substitution for Car Weight Reduction," SAE Paper 760023, February 1976.

3-2 R. Kaiser, "Automotive Applications of Composite Materials," Report No. DOT-HS-804745, Prepared by Argos Associates, Inc. Winchester, MA, July 1978.

3-3 R. T. Schwartz and D. V. Rosato, "Structural Sandwich Construction," p. 165-194 of "Composite Engineering Laminates," A. G. H. Dietz, Editor, The MIT Press, Cambridge, MA, 1969.

4.0 OTHER DESIGN CHARACTERISTICS OF METAL-PLASTIC LAMINATES

4.1 DENT RESISTANCE

Dent resistance is an important characteristic for any thin material especially if it has to be used in a visible outer panel where dents are unacceptable. Panel dent resistance depends on the yield strength, strain-rate sensitivity of the material, gage and panel stiffness. Dent resistance generally increases with increasing yield strength and panel gage, and decreases with an increase in panel stiffness. The relative dent resistance D has been defined as the energy required to produce a dent of a specified depth (4-1):

$$D \sim \frac{(\sigma_y t^2)^2}{S} \qquad (4\text{-}1)$$

where:

σ_y = material yield strength

S = panel stiffness

t = panel thickness

The panel stiffness, for an automotive panel, in turn is defined by the following relation

$$S \sim E\, t^n \qquad (4\text{-}2)$$

where:

E = flexure modulus of the panel

n = constant which depends on panel geometry, and which can range from 1 to 3. For many automotive panels, n = 2.

Substituting relation 4-2 into relation 4-1, with an assumed value of n=2, yields the following relation:

$$D \sim \frac{\sigma_y^2 t^2}{E} \qquad (4\text{-}3)$$

It is generally noted that the dent depth attained, h, is an inverse power function of the denting energy. If it is assumed that h varies as $D^{-\frac{1}{2}}$, then it follows that

$$1/h \sim D^{0.5} \sim \frac{\sigma_y t^2}{(E)^{0.5}} \qquad (4\text{-}4)$$

If both sides of relation 4-4 are multiplied by t, to obtain the dimensionless ratio t/h, relation 4-4 can be expressed as:

$$\frac{t}{h} \sim \frac{\sigma_y t^2}{(E)^{0.5}} \qquad (4\text{-}5)$$

According to equation 4-5, the ratio of dent depth to sheet thickness should vary as a function of the ratio of the product of the yield strength of the sheet material times the thickness squared divided by the square root of the flexure modulus. This relationship was used as a guide to compare the denting resistance of various metal-plastic laminates among themselves, and with homogeneous sheet materials.

DiCello (4-2) presented data on the dent depth of a number of steel-polypropylene-steel laminates of varying thickness, but of constant core volume ratio ($\alpha = 0.6$), as well as for other sheet materials used in automotive applications. In these tests, 25 cm^2 specimens were impacted dynamically with a standard Gardner Reverse Impact Tester. The impacter was one half pound (0.45 kg) in weight and had a one half inch (1.3 cm) spherical impact tip. The impact energy was varied from 1 in-lb (0.11 J) to 20 in-lb (2.26 J) by varying the drop height from 1 to 20 in (2.5 to 50.8 cm).

The results of these tests are presented in Figures 4-1 and 4-2. The results for a number of materials that could compete with 0.8 mm thick AK steel are given in Figure 4-1. The dent resistance of a 1.0 mm steel-polypropylene laminate is compared to that of sheets approximately 0.8 mm thick of the following materials: AK steel, re-phosphorized steel, H.S.-50 high strength steel, and aluminum alloy 5182-0.

For a given energy level, the aluminum alloy produced the deepest dent, and the H.S. 50 steel the shallowest. The other three materials were very close in dent resistance. These results indicate that a 1.0 mm thick steel-polypropylene laminate with 0.2 mm thick face sheets (with a T-1 temper) has a dent resistance comparable to an 0.8 mm thick AK steel sheet. The dent resistance of laminates increases as the thickness of the laminates is increased. This also applies to homogeneous materials, as shown in Figure 4-2.

DiCello's data at an energy level of 20 in-lb (2.26 J) were replotted in Figure 4-3 using Equation 4-5 as a guide. In this figure, the ratio of the dent depth to the sheet thickness, h/t, is plotted against $\sigma_y t^2/E^{0.5}$. A fairly good correlation is obtained in which it is observed that h/t decreases with $\sigma_y t^2/E^{0.5}$, as would be anticipated from Equation 4-5. There is scatter in the data for the thinner sheets, but surprisingly good agreement for the thicker materials.

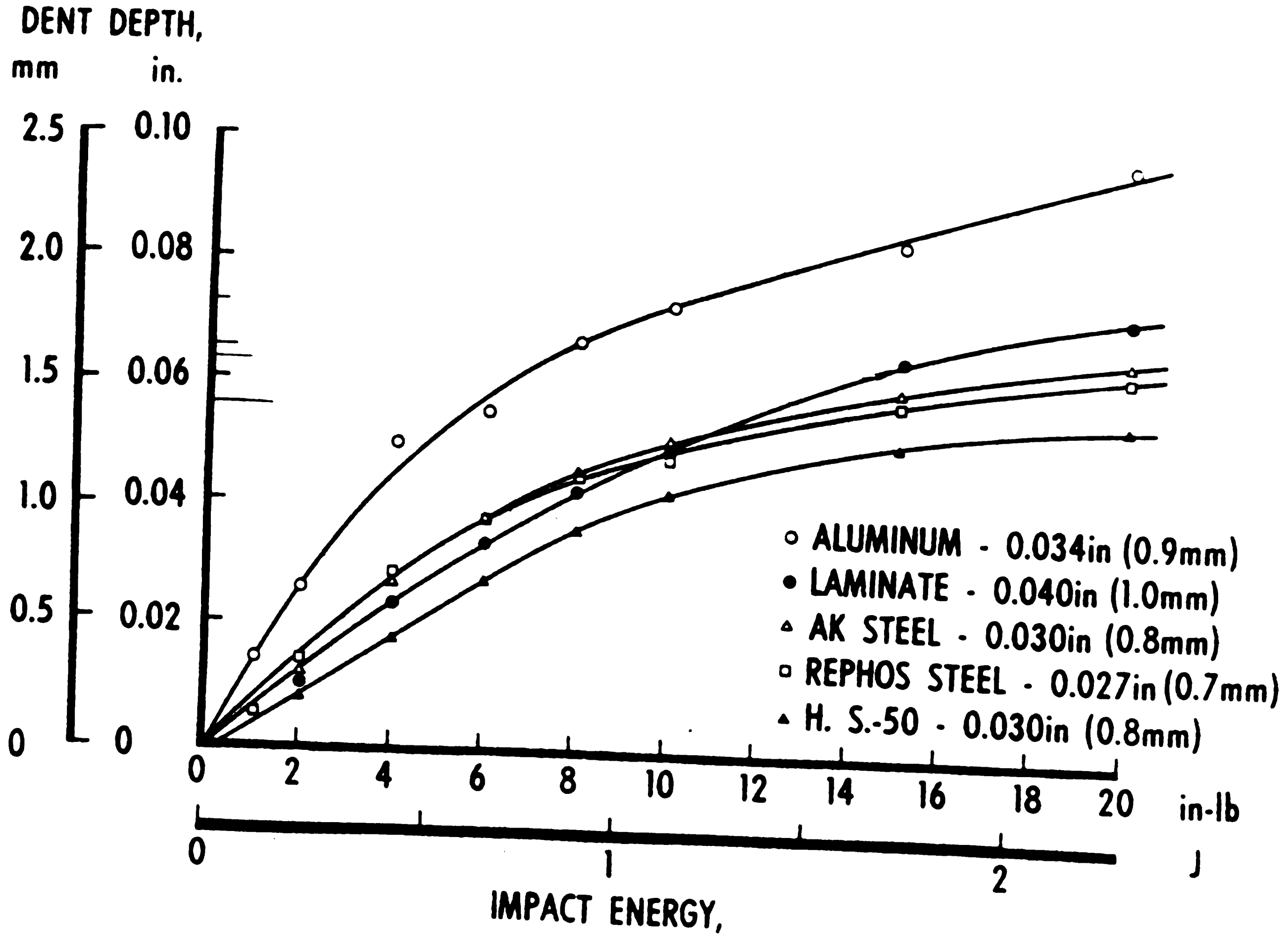


Fig. 4 -1Dent resistance of four potential body panel materials(Ref 4-2)

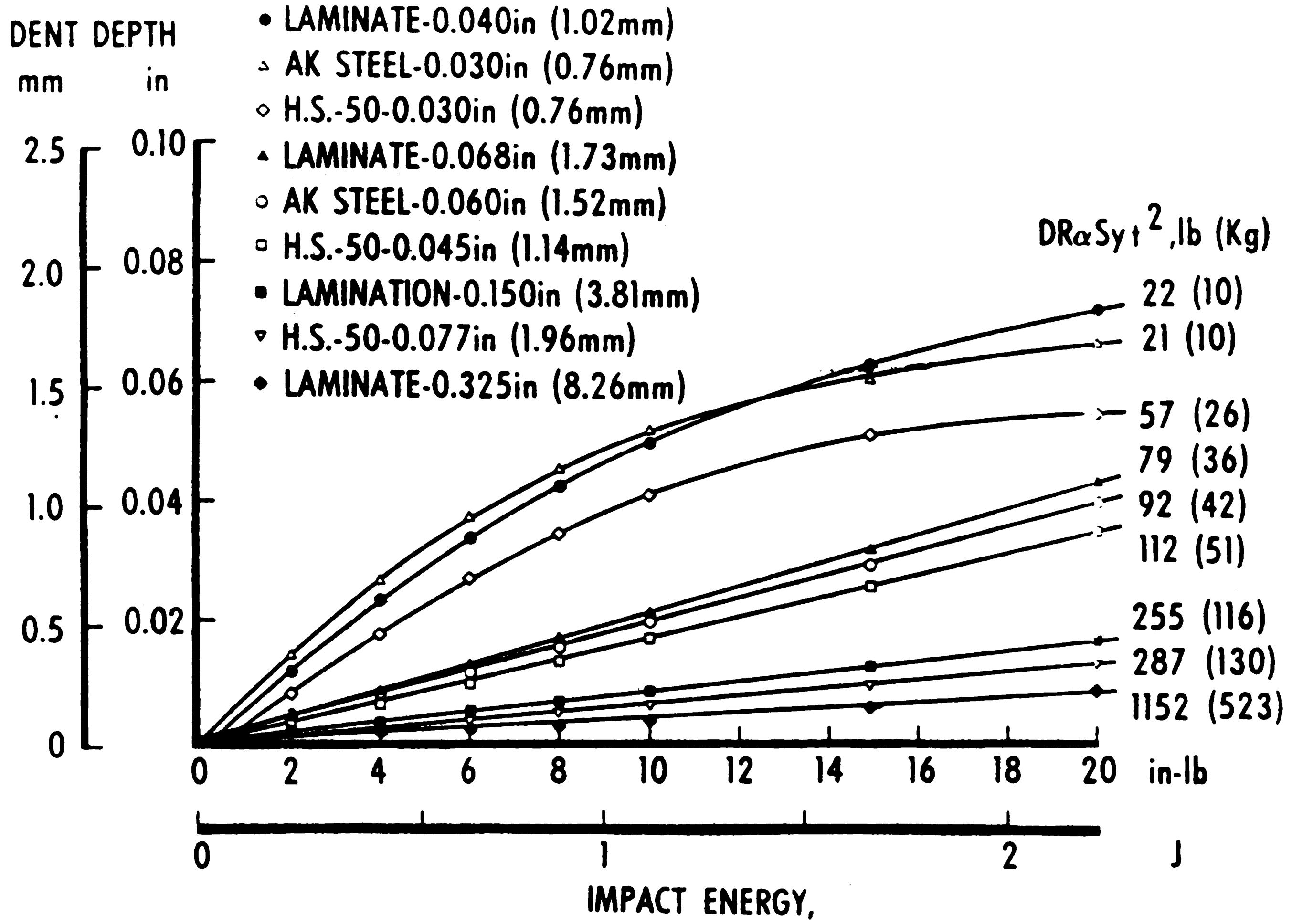


Fig. 4-2 Dent resistance comparison of a number of laminates and steels (Ref. 4-2)

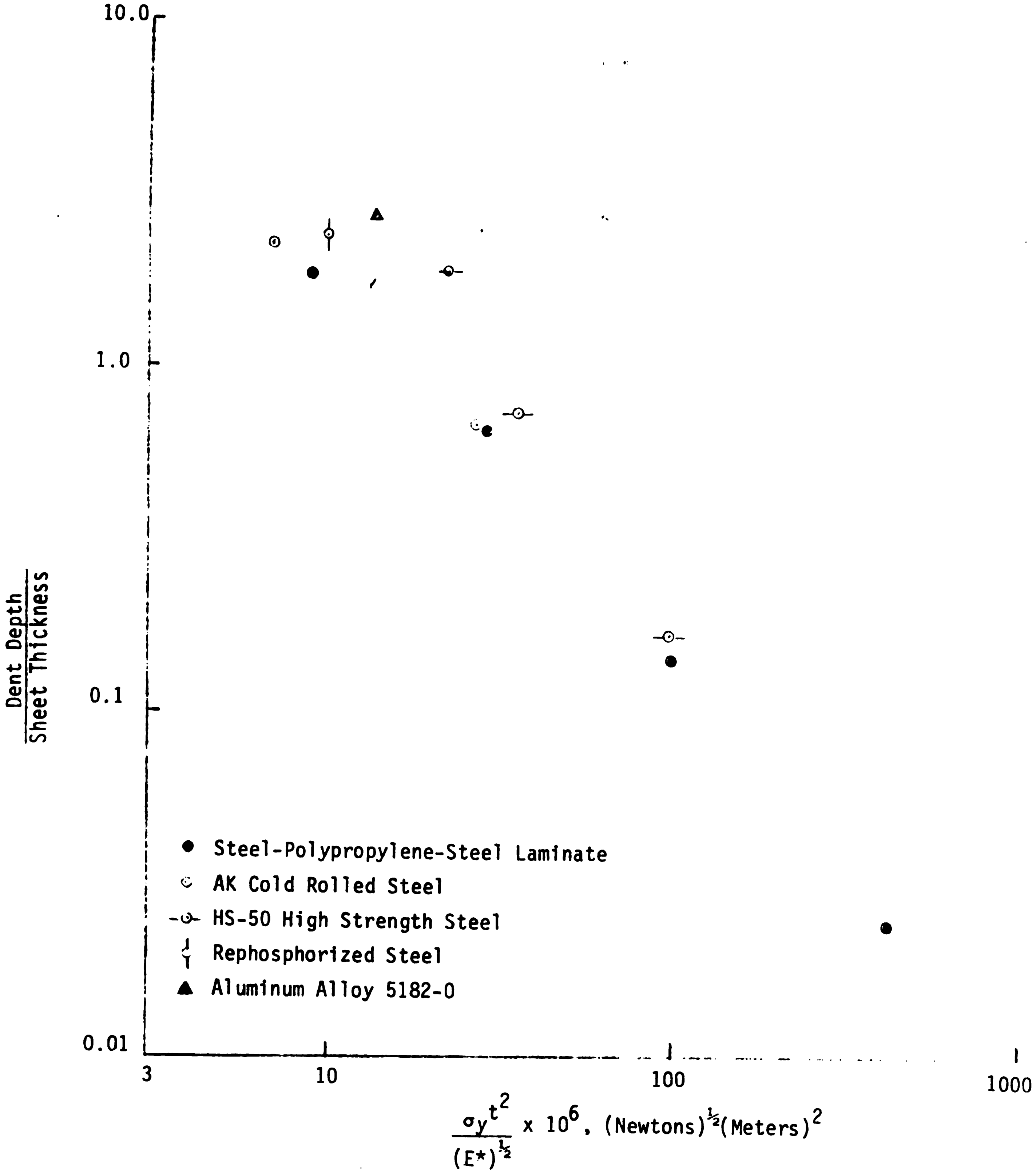


FIGURE 4-3. RATIO OF DENT DEPTH TO SHEET THICKNESS AS A FUNCTION OF MATERIAL PROPERTIES FOR VARIOUS MATERIALS OF INTEREST AS OBTAINED BY DI CELLO (REF. 4-2) (DENT DEPTH MEASURED AT 2.26 J (20 IN-LB))

Extensive measurements of the denting characteristics of a variety of metal-plastic sandwich laminates and of homogeneous metal sheets were also performed by J. C. Woodbrey of Monsanto Plastics and Resins Co. (4-3). Some of Woodbrey's results are presented in Tables 4-1 and 4-2, and in Figure 4-4 which is similar in format to Figure 4-3. Some of the dent depth data given in Tables 4-1 and 4-2 were previously published by McKenna et al. (4-4), but without including the yield strength data. Woodbrey examined the denting characteristics of a wide number of aluminum alloy (A.A.)-nylon laminates, A.A.-polypropylene laminates, steel-nylon laminates, steel-polypropylene laminates, various aluminum alloys, and various grades of steel. The dent depth measurements reported are the residual Gardner dent depths obtained after 20 in-lb (2.26 J) impact with a 0.5 lb weight (0.23 kg), 5/8 in (1.59 cm) in diameter, and with a 1.25 in (3.18 cm) anvil diameter.

In general, with the specified exception of the A.A. 1100-0 -nylon laminates, the data presented in Figures 4-3 and 4-4 are in agreement. If one were to overlay the two figures, the various points would overlap and fall in the same general pattern. In particular, the data for steel sheeting, aluminum sheeting, and steel-polypropylene laminates in both figures agree surprisingly well. In both cases, there is scatter in the steel data at low gages which reflects the fact that the difficulties of experimental life are not confined to any specific laboratory. In both figures, the data for aluminum tend to be higher than the trend line of the rest of the data. If the assumptions used as the basis of the analysis are correct, this is an indication that there is another factor which makes it appear that the aluminum alloys are somewhat less resistant to denting than would be expected on the basis of their thickness, yield strength and modulus. There may be a strain rate interaction in the case of the aluminum alloys which may not affect the other materials. However, these results could also be due to experimental scatter. In general, with the exception of the data for the A.A. 1100-0-nylon laminates, the rest of the data in Figure 4-4 can be considered to fall on a generally smooth curve, and the scatter that is present, may be attributed to experimental error, especially for the thicker samples (4-3). The curve defined by the data points for the 1100-0-aluminum-nylon laminate samples is significantly below the trend curve of all the other data points. The 1100-0 alumnium alloy-nylon laminates have a much lower residual dent depth than do the other materials in Figure 4-4 on the basis of thickness, yield strength and modulus. Woodbrey and his colleagues have postulated a springback mechanism to account for these findings. It is believed that compression of the nylon core during impact results in a subsequent springback action against the face sheet that reduces the depth of the dent formed with the fairly weak 1100-0 aluminum alloy.

The data presented in Figures 4-3 and 4-4 indicate that the denting characteristics of metal-plastic laminates, in general, depend on the same parameters that control the denting characteristics of homogeneous sheet metals, but that there are certain

TABLE 4-1 DENT DEPTH DATA FOR VARIOUS METAL-PLASTIC LAMINATES

CORE MATERIAL	FACINGS	THICKNESS OF FACINGS, t_f in.	TOTAL THICKNESS, t in.	EFFECTIVE FLEXURE MODULUS E*(a) 10^6psi	TENSILE YIELD STRENGTH, σ_y(b) 10^3psi	RESIDUAL GARDNER DENT DEPTH, h (c) in.	$\frac{h}{t}$	$\frac{\sigma_y t^2}{E \times 0.5}$ 10^6 (Newtons) ½ (meters)^2
Nylon 6-6	A.A. 3004-H19	.0062	.0597	5.0	8.93	.0529	0.886	24.0
Nylon 6-6	A.A. 3004-H19	.0062	.0630	4.8	8.55	.0481	0.763	26.3
Nylon 6-6	A.A. 3004-H19	.0062	.0633	4.8	7.53	.0467	0.738	23.4
Nylon 6-6	A.A. 3004 H19	.0062	.0648	4.7	10.4	.0440	0.679	34.1
Nylon 6-6	A.A. 3004 H19	.0062	.0671	4.6	8.81	.0406	0.605	31.7
Nylon 6-6	A.A. 5052 H38	.0052	.0595	4.4	8.19	.0515	0.866	23.4
Nylon 6-6	A.A. 5052 H38	.0052	.0615	4.3	8.37	.0520	0.846	26.1
Nylon 6-6	A.A. 5052 H38	.0052	.0613	4.3	9.65	.0500	0.816	29.8
Nylon 6-6	A.A. 5052 H38	.0052	.0727	3.7	8.72	.0390	0.536	40.6
Nylon 6-6	A.A. 1100-0	.0050	.0588	4.3	2.17	.0490	0.833	6.2
Nylon 6-6	A.A. 1100-0	.0050	.0633	4.0	2.06	.0450	0.714	7.0
Nylon 6-6	A.A. 1100-0	.0050	.0743	3.5	1.81	.0300	0.403	9.0
Nylon 6-6	A.A. 6061-T4	.0315	.1396	8.3	14.5	.0049	0.035	165.
Nylon 6-6	A.A. 6061-T6	.0064	.0567	5.4	10.2	.0450	0.794	24.0
Polypropylene(e)	A.A. 5052 H38	.0052	.0692	3.9	5.55	.0702	1.014	22.9
Polypropylene(e)	A.A. 5052 H38	.008	.0584	6.3	9.60	.0685	1.172	22.2
Nylon 6-6	C.R. Steel T-4	.0082	.0258	28.6	44.0	.0617	2.391	9.4
Nylon 6-6	C.R. Steel T-4	.0082	.0318	26.6	36.4	.0554	1.742	12.1
Nylon 6-6	C.R. Steel T-4	.0082	.0388	24.2	31.1	.0463	1.193	16.1
Nylon 6-6	C.R. Steel T-4	.0116	.0715	20.7	25.7	.0101	0.141	48.8
Nylon 6-6	C.R. Steel T-4	.0116	.1140	14.9	16.9	.0034	0.030	96.8
Polypropylene(e)	C.R. Steel T-4	.0116	.0720	21.4	21.5	.0220	0.306	41.8
Polypropylene(e)	C.R. Steel T-4	.0116	.1130	14.9	14.2	.0128	0.113	80.0
Nylon 6-6	C.R. Steel T-1	.010	.0360	27.4	22.1	.0520	1.444	9.32
Filled PP (f)	C.R. Steel T-1	.010	.0351	27.6	20.6	.0604	1.721	8.24
Polypropylene(g)	C.R. Steel T-1	.010	.0350	27.6	20.6	.0565	1.614	8.14
Polypropylene(e)	C.R. Steel T-1	.010	.0360	27.4	20.4	.0568	1.578	8.43

TABLE 4-1 DENT DEPTH DATA FOR VARIOUS METAL-PLASTIC LAMINATES. .(Continued)

NOTES:

a) Effective flexure modulus defined as $E^{*} = E_f (1 - \alpha^3)$
Where E_f = Flexure modulus of facings
α = Core volume ratio = $\frac{1-2\ t_f}{t}$

b) Tensile stress @ offset strain of 0.002 in/ in with 2 in initial gage length

c) Residual deformation often 20 in-lb Impact

d) Temper reported is that of facings before lamination

e) Shell 7129 polypropylene copolymer

f) Calcium carbonate filled, impact modified polypropylene

g) Shell 5220 polypropylene

Soure of Data: Reference 4-3

SOURCE OF DATA: Reference 4-3

MATERIAL	FLEXURE MODULUS, E 10^6psi	TENSILE YIELD STRENGTH, σ_y(a) 10^3 psi	SHEET THICKNESS, t in	RESIDUAL GARDNER DENT DEPTH, h(b) in	$\frac{h}{t}$	$\frac{\sigma_y t^2}{E^{0.5}}$ $(\text{Newtons})^{\frac{1}{2}}(\text{meters})^2$
ALUMINUM ALLOYS						
2036-T4 for Olds Delta 88 Hood	10	27.7	.0430	.0540	1.256	26.8
5052-H32	10	24.8	.0320	.0810	2.531	13.5
5052-H32	10	26.5	.0400	.0610	1.525	22.6
6009-T4	10	20.9	.0340	.0721	2.121	12.9
6009-T4 Heat Treated[c]	10	39.3	.0340	.0522	1.535	24.3
6061-T4	10	29.3	.0320	.0723	2.259	16.1
6061-T6	10	36.0	.0400	.0450	1.125	30.9
COLD ROLLED STEELS						
B 37 PK Rephosphorized Steel	30	38.9	.0270	.0573	2.122	8.8
Chevrolet Monte Carlo Hood Steel	30	27.2	.0333	.0505	1.517	9.3
Auto Body Steel	30	24.0	.0314	.0570	1.815	7.4
Oldsmobile Delta 88 Hood Steel	30	38.2	.0340	.0450	1.324	13.7
DPL-80 Inland High Strength Steel	30	62.5	.0200	.0540	2.700	7.8

a) Tensile stress @ offset strain of 0.002 in/in, with 2 in. initial gage length
b) Residual deformation after 20 in-lb impact
c) Heat treated 1/2 hr @ 400° F plus 1/2 hr @ 325° F.

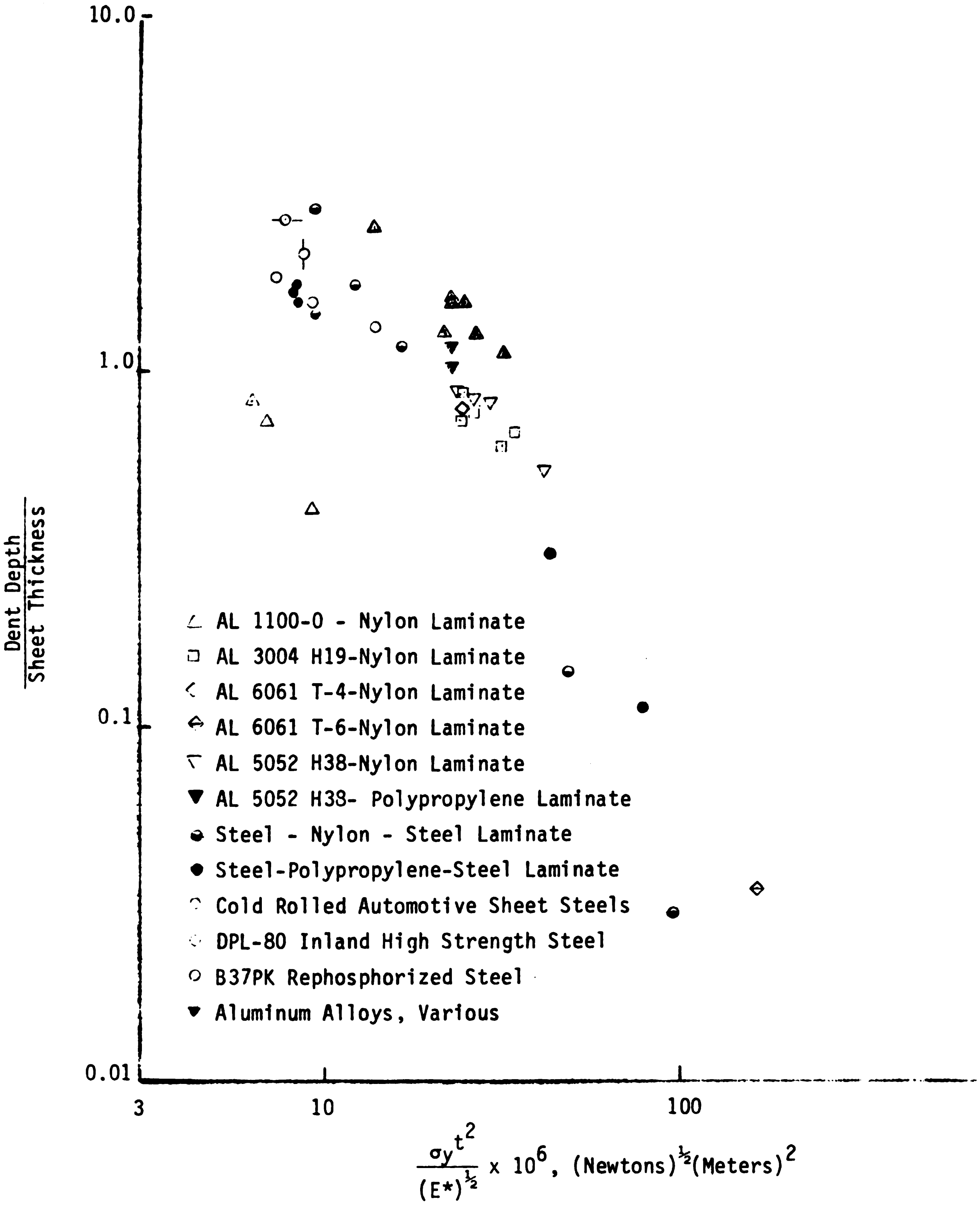


FIGURE 4-4 RATIO OF DENT DEPTH TO SHEET THICKNESS AS A FUNCTION OF MATERIAL PROPERTIES FOR VARIOUS MATERIALS OF INTEREST AS OBTAINED BY WOODBREY (REF. 4-3) (DENT DEPTH MEASURED AT 2.26 J (20 IN-LB))

instances, as when dealing with laminates that have relatively deformable face sheets, the denting resistance will be better than anticipated because of support provided the facings by the polymer core.

The results presented in Figures 4-3 and 4-4 allow one to compare laminates of different composition with each other and with steel on an equivalent weight basis. Equation 4-4 specifies the denting resistance of most materials that are of interest. According to this relation, for the denting resistance of a laminate (with hard face sheets) to be equal to the denting resistance of a steel sheet, it is necessary that:

$$\frac{\sigma_{yL} t_L}{(E_L)^{0.5}} = \frac{\sigma_{yS} t_S}{(E_S)^{0.5}} \qquad (4\text{-}6)$$

In the above, the subscript L refers to laminate properties, and the subscript S refers to the properties of steel.

Transposing terms, this equation can be rewritten as:

$$\frac{t_L}{t_S} = \frac{\sigma_{yS}}{\sigma_{yL}} \left(\frac{E_L}{E_S}\right)^{\frac{1}{2}} \qquad (4\text{-}7)$$

With

$$\frac{W_L}{W_S} = \frac{\rho_L t_L}{\rho_S t_S} \qquad (4\text{-}8)$$

where W_L and ρ_L, and W_S and ρ_S, are the weight per unit area and the density, of the laminate and steel respectively. By substituting for t_L and t_S in Equation 4-7, one obtains:

$$\frac{W_L}{W_S} = \frac{\rho_L \sigma_{yS}}{\rho_S \sigma_{yL}} \left(\frac{E_L}{E_S}\right)^{\frac{1}{2}} \qquad (4\text{-}9)$$

Values of W_L/W_S, as defined by Equation 4-9, are presented for selected aluminum faced laminates in Table 4-3, and for selected steel faced laminates in Table 4-4. These values of W_L/W_S compare the laminates with steel on the basis of equivalent dent resistance. This ratio will be referred to further in this discussion as $(W_L/W_S)_{DR}$, as distinct from the weight ratio based on equivalent flexural stiffness, $(W_L/W_S)_F$, as discussed in the previous chapter, and which is expressed as follows for a curved

TABLE 4-3 COMPARATIVE DENT RESISTANCE OF SELECTED ALUMINUM FACED LAMINATES

LAMINATE CORE	FACINGS(d)	CORE VOLUME RATIO, α	EFFECTIVE FLEXURE MODULUS, E^* (a) 10^6 psi	TENSILE YIELD STRENGTH σ_y (b) 10^3 psi	DENSITY gr/cm^3	EQUIVALENT LAMINATE TO STEEL WEIGHT RATIO		SOURCE OF DATA
						BASED ON DENTING RESISTANCE (h)	BASED ON FLEXURAL STIFFNESS (i)	
-	A.K. Steel	0	30	23.6	7.86	1.0	1.0	Ref.4-2
Nylon 6-6	A.A. 3004-H19	0.792	5	8.93	1.464	0.201	0.456	Ref.4-4
Nylon 6-6	A.A. 3004-H19	0.803	4.8	8.55	1.447	0.217	0.460	Ref.4-4
Nylon 6-6	A.A. 3004-H19	0.804	4.8	7.53	1.445	0.230	0.460	Ref.4-4
Nylon 6-6	A.A. 3004-H19	0.809	4.7	10.4	1.439	0.164	0.463	Ref.4-4
Nylon 6-6	A.A. 3004-H19	0.815	4.6	8.81	1.428	0.194	0.464	Ref.4-4
Nylon 6-6	A.A. 5052-H38	0.825	4.4	8.19	1.412	0.198	0.469	Ref.4-4
Nylon 6-6	A.A. 5052-H38	0.831	4.3	8.37	1.404	0.191	0.472	Ref.4-4
Nylon 6-6	A.A. 5052-H38	0.830	4.3	9.65	1.404	0.165	0.472	Ref.4-4
Nylon 6-6	A.A. 5052-H38	0.857	4.7	8.72	1.363	0.186	0.438	Ref.4-4
Polypropylene	A.A. 5052-H38	0.850	3.9	5.55	1.179	0.230	0.416	Ref.4-4
Polypropylene	A.A. 5052-H38	0.726	6.3	9.60	1.400	0.201	0.389	Ref.4-4
-	A.A. 5052-H38	-	10	24.8	2.70	0.189	0.595	Ref.4-4

<u>NOTES</u>:

a-b, d-g) = See Table 4-1
h) See Equation 4-9
i) See Equation 4-10

TABLE 4-4 COMPARATIVE DENT RESISTANCE OF SELECTED STEEL FACED LAMINATES

LAMINATE CORE	FACINGS(d)	CORE VOLUME RATIO, α	EFFECTIVE FLEXURE MODULUS, E^* (a) 10^6 psi	TENSILE YIELD STRENGTH σ_Y (b) 10^3 psi	DENSITY gr/lm^3	EQUIVALENT LAMINATE TO STEEL WEIGHT RATIO BASED ON DENTING RESISTANCE (h)	BASED ON FLEXURAL STIFFNESS (i)	SOURCE OF DATA
-	A.K. Steel	0	30	23.6	7.86	1.0	1.0	Ref.4-2.
Nylon 6-6	C.R. Steel T-4	0.364	28.6	44.0	5.411	0.360	0.705	Ref.4-4
Nylon 6-6	C.R. Steel T-4	0.484	26.6	36.4	4.605	0.357	0.622	Ref.4-4
Nylon 6-6	C.R. Steel T-4	0.577	24.2	31.1	3.980	0.345	0.564	Ref.4-4
Nylon 6-6	C.R. Steel T-4	0.676	20.7	25.7	3.320	0.322	0.508	Ref.4-4
Nylon 6-6	C.R. Steel T-4	0.796	14.9	16.9	2.508	0.314	0.453	Ref.4-4
Polypropylene (e)	C.R. Steel T-4	0.678	21.4	21.5	3.149	0.371	0.474	Ref.4-4
Polypropylene (e)	C.R. Steel T-4	0.795	14.9	14.2	2.337	0.348	0.422	Ref.4-4
Nylon 6-6	C.R. Steel T-1	0.444	27.4	22.1	4.873	0.631	0.649	Ref.4-4
Filled PP (f)	C.R. Steel T-1	0.430	27.6	20.6	5.038	0.704	0.697	Ref.4-4
Polypropylene (g)	C.R. Steel T-1	0.429	27.6	20.6	4.882	0.682	0.648	Ref.4-4
Polypropylene (e)	C.R. Steel T-1	0.444	27.4	20.4	4.771	0.671	0.635	Ref.4-4
PP Copolymer(h)	C.R. Steel T-1	0.550	25.0	14.6	4.038	0.758	0.563	Ref. 4-2
PP Copolymer(h)	C.R. Steel T-1	0.618	22.9	16.7	3.507	0.561	0.519	Ref. 4-2

NOTES: a-b, d-g) = See Table 4-1
h) See Equation 4-2
1) See Equation 4-
i) Hercules co-polymer

panel:

$$\left(\frac{W_L}{W_S}\right)_F = \frac{\rho L}{\rho S} \left(\frac{E_S}{E_L}\right) 0.5 \qquad (4\text{-}10)$$

Values of $(W_L/W_S)_F$ for the various laminates are also given in Tables 4-3 and 4-4. In these tables, the laminates are compared to automotive sheet steel with a tensile yield strength of 23.6 ksi (163 MPa), as reported by DiCello (4-2).

Referring to Table 4-3, in general, for aluminum faced laminages, $(W_K/W_S)_{DR} << (W_L/W_S)_F$, i.e. denting resistance is not a weight limiting criterion as compared to flexural stiffness. This is also the case for aluminum alloys, with AA 5052-H32 being reported as an example in Table 4-3. The low value of $(W_L/W_S)_{DR}$ is principally due to the low value of the modulus of aluminum, and aluminum faced laminates, the data reported in Table 4-1 indicate that nylon core laminates have better dent resistance than comparable polypropylene core laminates. This follows from the finding that the nylon core laminates have a higher yield strength than the polypropylene core laminates, and is reflected in the values of $(W_L/W_S)_{DR}$ presented in Table 4-3. The nylon core laminates have a lower value of $(W_L/W_S)_{DR}$ than do comparable polypropylene core laminates, in spite of the higher density of nylon cored laminates. This is believed due to a significant contribution to the tensile yield strength of the laminate by the nylon core.

The yield strength of a laminate can be expressed by the following:

$$\sigma_{yL} = \left(\frac{2t_F}{t_L}\right) \sigma_F^* + \left(1 - \frac{2t_F}{t_L}\right) \sigma_C^* \qquad (4\text{-}11)$$

where

σ_{yL} = yield strength of the laminate

σ_F^* = tensile strength of the face sheet at the laminate yield point.

σ_C^* = tensile strength of the core at the laminate yield point.

t_F = thickness of a face sheet

t_L = thickness of the laminate.

If the laminate core does not contribute significantly to the tensile properties of the laminate, then Eq. 4-11 reduces to the following expression:

$$\sigma_y{}^L = \frac{2t_F}{t_L} \sigma_y{}^F \qquad (4\text{-}12)$$

where σ_yF = yield strength of the face sheet.

Any significant effect of the polymer core on the tensile properties of a laminate can be quickly ascertained by calculating an apparent value of the yield strength of the face sheets, σ_{yaF}, from the experimental values of σ_{yL}, t_F and t_L. If σ_{yaF} is significantly greater than the published or experimental values of σ_{yF} for the face sheets, it follows that the polymer core contributes to the tensile properties. If σ_{yaF} is approximately equal to σ_{yF}, then the polymer core acts only as a spacer.

Published values of the tensile yield strength for aluminum alloy 5052-H38 range from 32 ksi (221 MPa) to 37 ksi (256 MPa) (4-25, 4-26). The average apparent yield strength of the face sheets for the four aluminum alloy 5052-H38/nylon 6-6 laminate samples listed in Table 4-3 was 53.5 ksi (370 MPa). The average apparent yield strength of the face sheets for the two samples of aluminum alloy 5052-H38/polypropylene laminate was 36 ksi (249 MPa). These results indicate that nylon 6-6 contributes significantly to the tensile properties of such laminates, whereas the polypropylene copolymer does not. Assuming a value of 37 ksi (256 MPa) for the yield strength of the laminate, it is estimated that the nylon core carries about 30 percent of the tensile load at yield, and a calculated value of 3.1 ksi (21.4 MPa) is obtained for the tensile strength of the nylon core at the yield point.

Comparable data for steel faced laminates are presented in Table 4-4. It is to be noted that $(W_L/W_S)_{DR}$ for steel faced laminates, in general, is significantly higher than the value of this ratio for aluminum faced laminates. This is a consequence of the higher modulus and higher density of steel. The temper of the steel facings has a very significant impact on $(W_L/W_S)_{DR}$. Laminates made with softer, more ductile T-1 temper facings have a much higher value of $(W_L/W_S)_{DR}$ than do laminates with steel facings with a T-4 temper. However, T-1 temper steels are much preferred for laminate use because of their better press forming characteristics.

For all the laminates listed in Table 4-4 with cold rolled steel with T-1 temper face sheets, and a polypropylene or polypropylene co-polymer core, it is noted that $(W_L/W_S)_{DR}$ has a higher value than $(W_L/W_S)_F$, i.e. with these materials, in those cases where dent resistance is of importance, it would be the weight limiting criterion, and not flexural stiffness. While for most samples, the difference between these equivalent weight ratios is less than 5% of the original steel weight, for the sample described in the next to last line of Table 4-4 (DiCello's (4-2) steel-polypropylene laminate 0.040 in (1.0 mm thick), the difference is nearly 20 percent. This laminate would offer only a weight savings of 24.2 percent based on denting as compared to 43.7 based on flexure.

While data were obtained for only one laminate with face sheets of cold rolled steel with a T-1 temper, and a nylon 6-6 core, these results indicate that, for this material composition as well, the nylon core contributes significantly to the dent resistance of the laminate. $(W_L/W_S)_{DR}$ for a T-1 temper steel/nylon 66 laminate is lower than the value of $(W_L/W_S)_{DR}$ for comparable laminates with a polypropylene core. Furthermore, for the nylon core laminate, $(W_L/W_S)_{DR}$ is somewhat lower than $(W_L/W_S)_F$. For this laminate, flexure remains the weight determining criterion.

In conclusion, while the denting characteristics of a laminate are principally established by the characteristics of the face sheets, the properties of the core can be of importance as well. For the laminates considered in the analysis, T-1 steel/polypropylene laminates were the only system for which dent resistance would be the weight limiting criterion. For all the other laminate systems examined, flexural stiffness remains the weight determining criterion for substitution of steel sheet.

4.2 DURABILITY AND ENVIRONMENTAL STABILITY OF METAL-PLASTIC LAMINATES

In order to be acceptable to the automotive equipment manufacturers, metal-plastic laminates must survive in the aggressive service environment that exposed automotive components are subjected to. The laminate has to survive as an integral structure over the lifetime of a vehicle. This implies that the metal face sheets, the polymer core, and the metal-plastic bond must not deteriorate, corrode or otherwise be altered so as to impair the functional characteristics of any component made from the laminate.

Specific environmental factors that can be identified include:

1. Deterioration of material properties with time.

2. Deterioration of material properties due to exposure to specific environments such as:

   - o <u>High temperatures</u> - temperatures in an automobile left in the sun in a tropical environment can reach 70°C (158°F) or more.

   - o <u>Low temperatures</u> - conversely an automobile can be exposed to temperatures of -40°C (-40°F) or even less during the depth of the winter in Northern regions of the U.S.

   - o <u>Water resistance</u> - automobiles must survive exposure to rain, and partial or temporary accidental immersion.

- Salt water exposure - vehicles used in the coastal states are exposed to a salt water environment, as are vehicles driven in the winter in the Northern parts of the country, where salt is used to melt road ice.
- Freeze-thaw cycling - as the temperature falls and rises above the freezing point, any water present on a vehicle will freeze and thaw periodically. This cyclic action, because of the expansion that occurs when water freezes, will be harmful to any material that has crevices.
- Gasoline and solvent exposure - any materials used for exposed panels, or under the hood must be resistant to automotive fuels, such as gasoline, gasohol and the like. Materials must be resistant to solvents and other agents normally used in vehicle maintenance.
- Etc., etc., etc.

3. Fire resistance.

With regards to the durability of laminates, it is necessary to consider the durability of each of the individual components, (the face sheets and the core) as well as the durability of the assembly. Nearly all the individual materials being considered as constituents of metal-plastic laminates for automotive use are well established materials for which extensive data bases exist. The varioua facing materials being considered are all commercial alloys. The polymer cores are mainly polymers already sold in high volume even though some polymers being considered, such as the polypropylene co-polymer promoted by Hercules, Inc. are materials for which this experience base does not yet exist. The stability of the metal-polymer bond and the resistance to events which require interaction between the face skins and the core are the major areas where there is current uncertainty with regards to the stability of metal-plastic laminates.

4.2.1 Face Skins

As far as the face skins are concerned, the major issue is corrosion, particularly of steel faced laminates. The corrosion of the face skins is of greater concern with a laminate than the corrosion of a homogeneous sheet because a given absolute penetration level results in a significantly greater proportional loss in the mechanical properties of the laminate. In applications where the integrity of both face sheets is required, the ratio of the useful life of a laminate to that of a homogeneous sheet (of the same composition as the face skin) would be expected to be proportional to the ratio of the thickness of face skin to the thickness of the homogeneous sheet. In certain circumstances, however, a laminate could be superior to a homogeneous metal sheet. For example, localized corrosion, e.g., pitting, could only progress to the plastic core and perforation would be prevented.

The potential for corrosion will depend significantly on the composition of the skins. Material options, in order of increasing corrosion resistance (and cost, as discussed in further depth in a subsequent chapter) include AK steel (as the reference case), electrolytic chromium coated AK steel, zincrometal coated steel, galvanized steel, aluminized steel, various aluminum alloys, and stainless steels.

4.2.2 Polymer Core

In terms of polymer stability, the major required characteristic is that the polymer remains functional at the extremes of the temperature range which a laminate can be subjected to in service.

High temperature stability: The data in Table 2-2 indicate that the polyethylenes have relatively low melting points (less than 140°C) and correspondingly low flexural deflection temperatures (in the range of 100°F to 190°F 38°C to 88°C) at 455 MPa. Hoffman's data on the effects of temperature on the mechanical properties of aluminum-low density polyethylene laminates indicate that the softening of the polymer results in a sharp drop in mechanical properties of the laminate at temperatures above 70°C - 75°C (158°G - 167°F) (4-5). As indicated in Table 2-4 the upper end of the useful temperature range of Alucobond is claimed to be 80°C (176°F). This preempts the use of laminates with a low density polyethylene core from use in under-the-hood applications where temperatures can reach 120°C (218°F) even for items not in direct contact with the block. There may be some question whether laminates with a low density polyethylene core could be used for external body panels if they have to be dimensionally stable under exposure to temperatures that can be attained in the Arizona desert at high noon on a hot summer day.

The comments made above should also apply to other polymers, such as high density polyethylene, ethylene vinyl acetate copolymers, and to polyionomer (Surlyn^{R}).

Polypropylene polymers have softening and melting temperatures that are about 30°C to 40°C higher than those of high density polyethylene. Polypropylene cored laminates should therefore also ahve useful operating temperatures that are about

30°C to 40°C higher than those of laminates with high density polyethylene cores, or approximately 105°C to 120°C (221°F to 248°F). Hercules, Inc. claims an upper use temperature of 250°F for Lite plate S^R steel-polypropylene laminates, which corresponds to the upper end of the above range (4-6). Such a laminate should be able to meet the upper temperature requirements of all body components, and of some under the hood applications. There may be some applications where the prevailing temperatures make a polypropylene core laminate marginal. Some developers, such as Bethlehem Steel Corp., are promoting the use of a highly filled polypropylene to raise the useful temperature an additional 20°C to 30°C, to 135°C to 150°C (275° to 300°F), depending on the formulation.

These temperature ranges apply to components that are not highly stressed. As indicated in Table 4-5, relaxation in applied transverse bolt stresses become important with increasing initial stress level and with increasing temperature as a result of creep of the polymer (polypropylene) core.

Nylon 6-6 exhibits significantly higher melt (T_m = 265°C (509°F) and stress deflection (T_{sd} = 245° (474°F)) temperatures than any of the other polymers listed in Table 2-2, and thus nylon cored laminates would be expected to have much higher use temperatures. McKenna and his colleagues at Monsanto (4-4) reported that formed aluminum-nylon 6-6 laminates did not distort significantly at a temperature of 191°C (376°F), as shown in Table 4-6, and also claimed distortion stability to temperatures in excess of 250°C (482°F).

Low Temperature Stability: All the polymers, listed in Table 2-2, with one exception, exhibit excellent stability and mechanical properties at low temperatures. The exception is polypropylene, or its derivatives, which characteristically has poor low temperature impact properties. The lower end of the useful temperature range claimed for laminates are -48°C (-55°F) for Alucobond^R polyethylene core laminates as indicated in Table 2-4, -55°C (-75°F) for aluminum-nylon laminates (4-4), and -51°C (-60°F) for steel polypropylene laminates (4-6). The last value of -51°C (-60°F) is the one reported by Hercules Inc. in its brochure on Liteplates^{TM} steel-plastic laminates. Significantly, poorer impact properties were observed for aluminum-polypropylene laminates by McKenna et al., as shown in Table 4-7. Comparisons between the Hercules and Monsanto results are difficult to make because the particular grade of polypropylene used is of critical significance. A. Brachman (4-7) stated that in order to be able to retain acceptable low temperature characteristics for the Bethlehem Steel Corp. steel-filled polypropylene laminates, the formulation required the incorporation of an impact additive.

Moisture and Solvent Resistance: All the polymers that have been considered as candidate core materials, exhibit good

TABLE 4-5

EFFECT OF APPLIED STRESS LEVEL AND TEMPERATURE ON BOLT STRESS RELAXATION WITH STEEL-POLYPROPYLENE LAMINATES AFTER A SEVEN WEEK PERIOD

LAMINATE THICKNESS	INITIAL APPLIED STRESS LEVEL	STRESS LEVEL AFTER 7 WEEKS		
		ROOM TEMP.	66 °C	116 °C
MM	MPa	MPa	MPa	MPa
1.02	108	70	68	46
	52	48	47	34
	29	28	28	25
8.26	108	58	44	28
	52	30	30	18
	29	23	22	14

SOURCE : J.A. DI CELLO, SAE PAPER 800078 (Ref. 4-2).

TABLE 4-6

HIGH TEMPERATURE DISTORTION OF ALUMINUM - NYLON LAMINATES

MATERIAL	FORMING TEMPERATURE °C	SPRINGBACK OF OLSON CUP SAMPLES AFTER ½ HOUR EXPOSURE AT 191°C (376°F) PERCENT
6061-O ALUMINUM NYLON LAMINATE	76	-.9
6061 - "T4" ALUMINUM/ NYLON LAMINATE	76	+.8
REFERENCE HOOD STEEL	23	0
HOOD ALUMINUM	23	-.2

SOURCE : L.W. MC KENNA ET AL., SAE PAPER 800079 (Ref. 4-4).

TABLE 4-7

LOW TEMPERATURE IMPACT STRENGTH OF METAL-PLASTIC LAMINATES

LAMINATE COMPOSITION	THICKNESS	IMPACT STRENGTH AT - 32°C
	M	N
5052-H 38 ALUMINUM/NYLON	1.45	18.1
6061-T 4 ALUMINUM/NYLON	1.42	11.3
6061-T 6 ALUMINUM/NYLON	1.50	18.1
6061-0 ALUMINUM/POLYPROPYLENE	1.60	0.6
6061-T6 ALUMINUM/POLYPROPYLENE	1.42	0.7

SOURCE: L.W MC KENNA ET AL, SAE PAPER 800079 (Reference 4-4) resistance to hydrocarbons and other solvents, except for polyionomer which is sensitive to alcohols and swells in hydrocarbons. Referring to Table 2-2, the polymers which contain polar groups all exhibit greater moisture absorption than the nonpolar polyolefins. The polymers which tend to absorb moisture include nylon 6-6, polyethylene-vinyl acetate co-polymer, polyionomer, and most likely as well, the self-adhering polypropylene copolymer which Hercules Inc. is developing for laminate use. The characteristics that would be imparted to the polypropylene to make it wet and adhere to steel will promote water absorption. The low level of water absorption that will occur in service with these polymers will tend to plasticize them to a slight extent, as indicated for nylon 6-6 in Table 2-2, but should not cause any major deterioration or alteration of the bulk properties of the polymer core. The presence of water may be more significant, however, in terms of potentially interferring with the bond at the metal-polymer interface, as discussed in section 4.2.3.

U-V Radiation and Sunlight: Since the core is exposed to the environment only at the edges of a laminate, only a negligibly small fraction of a core would be exposed to sunlight and ultraviolet radiation, which, for many polymers, particularly the polyolefins, contributes significantly to long term polymer degradation. The presence of the face sheets which act as barriers makes this a non-issue.

Flammability: The nature of the polymer core and its aspect ratio establish the flammability characteristics of a metal-plastic laminate. No data have been obtained as of yet on the flame characteristics of laminates designed for automotive use.

Flammability data obtained on Alucobond and Planium aluminum-polyethylene laminates indicate no special flammability problem, especially for the thinner laminates. It is to be noted that these laminates have been approved for use as building materials. Planium 2100 (with a total thickness of 2 mm and 0.1 mm face sheets) has been approved as a flame retardant material under the Japan Building Standards Act, while the other thicker laminates listed in Table 2-8 (Planium 2200, 3200 and 4200) have been approved as semi-combustible materials (4-8).

Alucobond material tested in concordance with ASTM designation E-84-76A (Tunnel Test) performed as follows:

THICKNESS	FUEL CONTRIBUTION	SMOKE DENSITY	FLAME SPREAD
3mm	0	15	5
4mm	0	50	10

The resultant building materials surface burning classifications are National Fire Protection Association Class A and United Building Code Class I for each of these panels (4-9).

Extrapolating the above to the thinner laminates that are being considered for automotive construction, one would expect them to exhibit yet better flame resistance as a class. Specific variations can be expected with the nature of the particular polymer and the value of the core volume ratio, α. As α decreases, flame resistance should improve. Further work, however, is required to better define the flammability and flame spread characteristics of metal-plastic laminates being considered for automotive applications.

4.2.3 Core-Face Bond

According to Miller (4-10), the strength of the core-face bond is not highly critical for the development of the desired laminate properties. He reports that the stiffness of experimental laminates made with bond peel strength as low as 8 N/cm (14 lb/in) was equal to the theoretical stiffness one would expect from geometrical considerations. Failure of such a bond has not been observed in destructive mechanical tests, the faces, and then the core, fracture without discernible delamination. Miller further states, however, that the most critical requirement of the bond, and of the core, will be its resistance to aging, aggressive environments, and both elevated and low temperatures. It is hard to disagree with this statement.

The peel strength data that have been reported in the literature for various metal plastic laminates are presented in Table 4-8. These values are all well in excess of Miller's minimum value.

Limited aging, weathering and environmental exposure data have been obtained for some of the laminates. The most extensive data base has been obtained for the thicker laminates, developed for architectural purposes. Consolidated Aluminum Corp. reports that no appreciable loss of bond strength has been determined due to weather conditions (4-9). Mitsui Petrochemicals Industries Ltd. reports that the residual peel strength of Planium laminates subjected to various temperature cycles was at least 90% of the original value, as shown in Table 4-9. Planium laminates also retained 80% of their original peel strength after having been subjected to 1000 hours of accelerated weathering in a weatherometer test. Specific test conditions were not reported (4-8).

The results of accelerated aging tests on the strength of skin-core bond for aluminum-nylon 6-6 laminates are presented in Table 4-8. According to McKenna et al., in these tests, the samples were completely immersed and in some cases, one skin was removed to increase the test severity. It is to be noted that

TABLE 4-8

REPORTED VALUES OF SKIN-CORE BOND PEEL STRENGTH FOR REPRESENTATIVE METAL PLASTIC-LAMINATES

LAMINATE SYSTEM	SKIN-CORE BOND PEEL STRENGTH N/cm (lb/in)	REFERENCE
Aluminum-Nylon		
Min	87.6 (50)	4-4
Max	122 (70)	
Aluminum H.D. Polyethylene		
Planium 2100	38.5 (22)	4-8
Planium 4200	61.3 (35)	
Aluminum L.D. Polyethylene		
Alucobond	26 (46)	4-9
BASF Development Laminates	127 (73)	
Steel-Polypropylene		
Self adhering Co-polymer	53-350 (30-200)	4-11
ECS Steel-Polypropylene		4-12
Morprime Bonded Homopolymer		
Polymer A	75[a] (43)	
Polymer B	114[b] (65)	
Polymer C	131[b] (75)	
Polymer D	226[b] (129)	
Polymer E	256[b] (146)	

[a] Failure by delamination

[b] Cohesive failure of the polymer

TABLE 4-9

ENVIRONMENTAL STABILITY OF ALUMINUM/NYLON LAMINATES

ENVIRONMENT	TEMPERATURE °C	TEST DURATION MONTHS	CHANGE IN ADHESION* PERCENT
WATER	23	17	-2
WATER**	23	12	+6
10% NACL SOLUTION	23	11	+8
10% $CACL_2$ SOLUTION	23	11	+11
AIR	100	2	+22

* AS INDICATED BY SKIN/CORE PEEL STRENGTH

** ALUMINUM SKIN REMOVED FROM ONE SIDE

SOURCE : L.W. MC KENNA ET AL, SAE PAPER 800079 (Reference 4-4) after very long exposures the adhesion level remains stable in both water and saline solutions. After two months of exposure to hot air, measurable increase in adhesion was observed. Similar tests were also conducted in cyclic environments involving ultra-violet exposure, thermal cycling and intermittent salt spray and no effect on adhesion after a period simulating one year of outdoor exposure was observed. It was further reported that outdoor exposure samples in Florida and Arizona have not demonstrated any detectible change in integrity after six months, nor do test coupons mounted on the chassis of vehicles operating in the St. Louis area.

In comparison to the information reported for aluminum faced laminates, minimal data were reported with regards to the effects of various environments on the stability of the metal-plastic bond for steel faced laminates. A. Brachman reported that Bethlehem Steel Corp.'s adhesively bonded, ECC steel-filled polypropylene laminates survived standard 1000 hr. salt spray test (4-7). These laminates also survived the thermal cycle test in which the temperature was cycled 4000 times between -20°F and +150°F (-29°C to +66°C). Schultz reported on salt spray tests with laminates that had a series of holes drilled through the faces to expose the face skin-polymer core bond line. These laminates had ECC steel faces bonded with Morprime^R adhesive to various polypropylene cores. No noticeable change in the peel strength of the laminates was observed as a result of the salt spray tests (4-12).

The paucity of information on the peel strength of mild steel faced laminates is disconcerting especially when one considers that steel is subject to oxidation under ambient conditions, and that the rust (iron oxide) formed is porous and has poor mechanical properties. Incipient corrosion of steel at the metal-plastic interface may result in delamination. An associated problem would be the migration of moisture at the skin-core interface. If there were any significant presence of moisture at the interface, exposure of the laminate to repeated freeze-thaw cycles might result in rapid deterioration of the interfacial bond and subsequent delamination. If moisture can migrate along the bond line, then one is also faced with the potential presence of salt at the inner face of a laminate skin, resulting in premature corrosion from the inside.

There is also uncertainty for any laminate as to whether standard peel tests performed with flat panels (for ease of measurement) would provide information that would be representative for formed shapes. The stresses induced by the stamping of sheet stock into a formed shape have to have an effect on the core-skin bond. The environmental resistance of shaped laminate may well be different than might be predicted from peel tests with flat panels.

Thermal Stresses: The coefficient of linear thermal expansion of the metal faces is significantly less than that of the polymer cores. The coefficients of linear expansion for the polymers listed in Table 2-2 range from about 50 x 10^{-6} cm/cm°C to 200 x 10^{-6} cm/cm/°C, as compared to 11 x 10^{-6} cm/cm/°C for steel and 23 x 10^{-6} cm/cm/°C for aluminum. When subjected to a given change in temperature, the core would normally tend to expand or contract more than the face skins. The laminates of current interest all have relatively thick face skins which are strong enough to restrain the expansion of the polymer core, so that the coefficient of thermal expansion is essentially that of the face skins. This results in the development of a shear stress at the metal core interface. These stresses are normally present in a laminate at ambient temperatures since the laminates are normally formed at temperatures high enough to melt the polymer core. The results of thermal cycling tests on aluminum faced laminates presented in Table 4-7 indicate that temperature induced interfacial stress did not contribute to delamination. It would be necessary to obtain similar data for steel faced laminates, especially in conjunction with the presence of moisture, with the temperature cycle passing through the freezing point of water.

More significant thermally induced stresses may occur when the laminate is subjected to a severe temperature gradient across its thickness, because of the thermal insulating properties of the core. In this case, there will be differential expansion of one face sheet with respect to the other. This will cause "bowing" of simply supported panels, and restraint of such "bowing" at intermediate supports in continuous panels. Such restraints result in very significant thermally induced bending and shear stresses within the laminate. This problem has arisen with the use in the Arctic of prefabricated structural sandwich panels using steel facings bonded to a polyurethane foam core (4-12).

It could also arise with the thermoplastic core laminates of interest in certain under the hood applications, such as valve covers. Further data are still required to scope out this potential problem area.

4.3 CRASHWORTHINESS OF METAL-PLASTIC LAMINATES

At the moment, there is little information on the behavior of metal plastic laminates in a crash situation. It can be argued that since there is less metal in the cross-section of a laminate than in a steel sheet of equivalent stiffness, the energy absorption capability of the laminate will be less than that of the steel sheet. It can also be argued that a laminate might have higher energy absorption capability than a steel sheet of equivalent thickness. In part, this may occur because of the higher yield and tensile strengths of the facing sheets of the laminate than those of the sheet steel of equivalent stiffness. Furthermore, since the facings are supported by the core, their yielding may occur in a more efficient manner than that of a sheet steel of equivalent stiffness.

Some preliminary crushing impact tests were performed on metal plastic laminates at the Budd Technical Center. Based on these results, metal plastic laminates do not appear to offer any significant cost or weight advantage over sheet steel in terms of their crashworthiness (4-14).

4.4 DESIGN LIMITATIONS DUE TO WIDTH/THICKNESS AVAILABILITY OF FACING MATERIALS

Because of manufacturing constraints, there are width and thickness limitations on sheet materials that are available commercially. The maximum width of the sheets that could be used as facing materials establish the maximum width of the laminates that can be produced. In general, the maximum width of sheet material that is available commercially decreases as the thickness of the sheet decreases. Table 4-10 summarizes the width restrictions as a function of thickness for annealed sheet steel based on the manufacturing practice of the five major steel producers contacted during the study (Bethlehem Steel Corp., Inland Steel Co., National Steel Corporation, Stelco, Inc. and U.S. Steel Corporation). Because of the increased hazard of pressure welding ("sticking") in annealing ovens, sheet steel less than 0.2 mm thick is only available "as-rolled." The minimum thickness of sheet steel that is currently commercially available in the U.S. is 0.14 mm, i.e., 50 lb. per base box black plate in the parlance of the industry.

Aluminum sheet products less than 0.15 mm (0.006 in) thick are sold as foil, and thicker material is sold as sheet. Aluminum foil is available in widths of up to 60 in. (152 cm) but only for aluminum alloys 1100 and 1145 which do not have optimal mechanical properties for use in laminates (4-4). Width-thickness limitations for coiled aluminum alloy sheet are summarized in Table 4-11. In many cases, the availability of heat treatable alloys in zero tempers is similar to that of the non-heatable alloys. It is to be noted that while non-heat treatable alloys are available in sheets as thin as 0.14 mm (0.006 in), the minimum thickness in which heat treated tempers of heat treatable alloys are available is 0.20 mm (0.008 in).

Width limitations only apply to laminates which incorporate face sheets less than 0.30 mm to 0.36 mm (0.012 in. to 0.014 in.) thick for example, since 0.38 mm (0.015 in.) thick sheets, 152 cm (60 in) wide are available. This is sufficient for most automotive applications.

The width limitations on the face sheets do apply to laminates designed to replace sheet steel approximately 0.8 mm (0.032 in.) thick in a variety of automotive components. At the moment,

TABLE 4-10

REPRESENTATIVE WIDTH/THICKNESS LIMITATIONS ON CURRENT COMMERCIAL AVAILABILITY OF COILED SHEET STEEL IN THE U.S. AND CANADA

THICKNESS RANGE MM (IN)	MAXIMUM AVAILABLE WIDTH CM (IN)
0.14 - 0.20*(0.006-0.008*)	86 - 102 (34 - 40)
0.25 - 0.38 (0.010-0.015)	91 - 122 (36 - 48)
0.38 - 0.51 (0.015-0.020)	122 - 152 (48 - 60)
0.51 (0.020) and above	182 - 193 (72 - 76)

* Sheet Steel less than 0.20 mm (0.008 in) thick only available in as-rolled condition.

TABLE 4-11

REPRESENTATIVE WIDTH/THICKNESS LIMITATIONS ON CURRENT COMMERCIAL AVAILABILITY OF COILED ALUMINUM ALLOY SHEETS

NON-HEAT TREATABLE ALLOYS COIL (1)	0.14 - 0.28 (0.006-0.011)	91 - 127 (36 - 50)
	0.28 - 0.36 (0.011-0.014)	102 - 127 (40 - 50)
	0.36 - 0.41 (0.014-0.016)	102 - 152 (40 - 60)
	0.41 - 0.61 (0.016-0.024)	122 - 168 (48 - 66)
	0.61 - 0.89 (0.024-0.030)	168 - 244 (66 - 96)
	0.89 - 1.29 (0.030-0.051)	244 - 259 (96 -102)
HEAT TREATABLE ALLOYS HEAT TREATED TEMPERS COILS (2)	0.20 - 0.30 (.008-.012)	122 (48)
	0.30 - 0.41 (.012-.016)	152 (60)
	0.41 - 2.1 (.016-.082)	160 (63)

1) Based on discussions with sales representative of Aluminum Company of American, Reynolds Aluminum Co., and Kaiser Aluminum Co.

2) Kaiser Aluminum Corp., "Mill Products Availabilities" MP2,8/72 (Reference 4-15)

steel faced laminates cannot be used to manufacture components where the minimum blank dimension is more than approximately 100 cm (39 in.). With aluminum faced laminates, the minimum blank dimension cannot be greater than 122 cm. to 127 cm. (48 in. to 50 in.) depending on the alloy required. This precludes laminates from being considered for many larger automobile or light truck panels currently stamped from 152 cm (60 in.) wide sheet steel.

The limitations on the width and thickness of commercially available sheet metals reflect current demands of the market place rather than any inherent technical limitations in the manufacture of either thinner and/or wider sheet material. Most of the thin sheet steel and aluminum now sold are used by the packaging industry which does not require a wide product. Much of the sheet steel rolled to gauges of less than 0.012 in. (0.30 mm) is tinned. It has to be narrow enough to pass through the tinning lines which are designed to accommodate a sheet less than 100 cm (39 in.) wide.

In 1960, Stone reviewed the rolling of very thin tinplate (4-16). Calculations were presented that projected that 0.0040 in. (0.10 mm) thick steel sheet could be rolled at 5000 ft/min (1500 m/min) on a conventional 5 stand tandem cold mill with 24 in. (61 cm) work rolls. These calculations were supported by test data on the rolling of a 0.0044 in. (0.11 mm) thick steel sheet, 29 in. (74 cm) wide, on a 23 in. (58 cm) and 56 in. x 52 in. (142 cm x 132 cm) five stand mill at a rolling speed of 4400 ft/min (1340 m/min). Stone proposed a number of alternative methods of producing thinner gauge steel at high rates than was the current practice in 1960, and which would still be valid today. These included the use of a six stand mill, double reduction through a five stand mill, with or without intermediate annealing, or the rolling of two thicknesses of strip through a five stand mill, similar to the usual practice in the very thin aluminum foil field.

As far as technical feasibility, there are three issues:

a. Is it possible to roll thinner sheet steel than is current practice?

b. Is it possible to roll wider sheet steel than is current practice?

c. Is it possible to anneal thinner, wider material?

There are sufficient data to demonstrate that it is possible to produce thineer and wider, fully annealed steel sheet than is current practice.

In 1964, U.S. Steel Corp. announced the commercial availability of annealed steel foil in thicknesses of from 0.0035 in.

(0.089 mm) down to 0.001 in. (0.025 mm) in sheet widths as high as 42 in. (107 cm) (4-17, 4-18). The foil was produced on a one stand, four high, hydraulically operated mill. Methods of box annealing were developed to overcome sheet adhesion. Some of the more important mechanical properties of this material are given in Table 4-12. In larger coils, the commercial price (1970) for uncoated steel sheet, 0.002 in. (0.051 mm) thick was \$0.21/lb (\$0.46/kg.) or 1.66¢/ft^2 (17.9C/m^2). Adjusting for inflation (using the ratio of the 1980 price of black plate to its 1970 price, or 3.5), the current price of this foil would be \$0.74/lb. (\$1.62/kg.) or 5.81¢/ft^2 (\$0.63/m^2). The product was discontinued in the mid 1970's because of a lack of a sufficient market (4-19).

A wide variety of thick gauge alloys, including hard to roll refractory alloys, are produced in thin gauge sheet form on Sendzimir cold rolling mills. Sendzimir mills differ from conventional rolling mills principally in the size and method of support of the work rolls. A Sendzimir mill uses small diameter work rolls, usually less than 10 cm. (4 in.) in diameter, that are fully supported along their length by intermediate rolls and backup assembly, as indicated in Figure 4-5. In comparison to the Sendzimir cold rolling mills, conventional mills use larger diameter work rolls and back up rolls, which are individually supported by their necks in two separate housings. Under rolling pressure, there is less variation in roll deflection in a Sendzimir mill than in a conventional mill, allowing for greater ease of control in thickness variation. As a result, there are no inherent width limitations in a Sendzimir mill. By using a smaller diameter work roll, it is possible to achieve a greater degree of reduction in thickness per pass, and ultimately also achieve a thinner gauge product. Conversely, the use of a smaller work roll results in lower operating mill speed (4-20).

Sendzimir mills have found wide use in the rolling of stainless steel and refractory alloys, such as titanium and nickel alloys, where high surface finish, close gauge tolerance and high reduction without intermediate annealing have been necessary. A number of Sendzimir mills have been built for rolling low carbon-steel, dating back to 1932. The acceptance specifications for the 50 in. (127 cm.), or wider, Sendzimir mills listed in Table 4-13 included the production of maximum width carbon steel sheet in thicknesses of 0.2 mm (0.008 in.) or less. Similar mills installed in the United States for carbon steel use include a ZR 21-55 Sendzimir mill at Sharon Steel corp. in Sharon, Pennsylvania; a ZR 22BB-50 Sendzimir mill at National Rolling Mill, in Malvern, Pennsylvania; and a ZR 21B-44 at Granite City Steel, Granite City, Illinois (4-21). It should be noted that when asked about the availability of their thinnest-widest product, a sales representative of National Rolling Mills was willing to quote without reservation on 0.010 in. (0.25 mm), 48 in. (122 cm) sheet steel of commercial quality temper and bright finish. The company was not prepared to quote on thinner gauge material at the time (4-22).

TABLE 4-12

MECHANICAL PROPERTIES OF TIN-COATED AND PLAIN STEEL FOIL OF DIFFERENT THICKNESSES IN THE AS-ROLLED AND ANNEALED CONDITIONS *

Thickness	0.0035in	0.0030in	0.0025in	0.0020in	0.0015in	0.0010in
Tensile strength (ASTM D929)						
longitudinal lb/in^2	105 000 (50 000)	105 000 (45 000)	105 000 (45 000)	105 000 (45 000)	105 000 (45 000)	105 000 (45 000)
transverse lb/in^2	115 000 (50 000)	105 000 (45 000)	105 000 (45 000)	105 000 (45 000)	105 000 (45 000)	105 000 (45 000)
Yield strength (ASTM D828)						
longitudinal lb/in^2	105 000 (40 000)	100 000 (35 000)	100 000 (35 000)	100 000 (35 000)	100 000 (35 000)	100 000 (35 000)
transverse lb/in^2	105 000 (40 000)	100 000 (35 000)	100 000 (35 000)	100 000 (35 000)	100 000 (35 000)	100 000 (35 000)
Elongation (ASTM D987) longitudinal and transverse per cent in 2in	2.0 (30)	2.0 (30)	1.5 (30)	1.0 (20)	1.0 (12)	1.0 (5)
Drawing. Olsen cup depth in	0.08 (0.29)	0.06 (0.27)	0.06 (0.26)	0.06 (0.24)	0.05 (0.22)	0.04 (0.15)
Impact strength (ASTM D781) beach puncture, in oz/in	70 (130)	55 (100)	35 (70)	30 (50)	15 (25)	10 (10)
Burst strength (ASTM D374) Mullen lb/in^2	430 (510)	300 (390)	210 (315)	200 (270)	100 (165)	65 (75)

* Annealed Figures in brackets

Soure: Reference 4-17

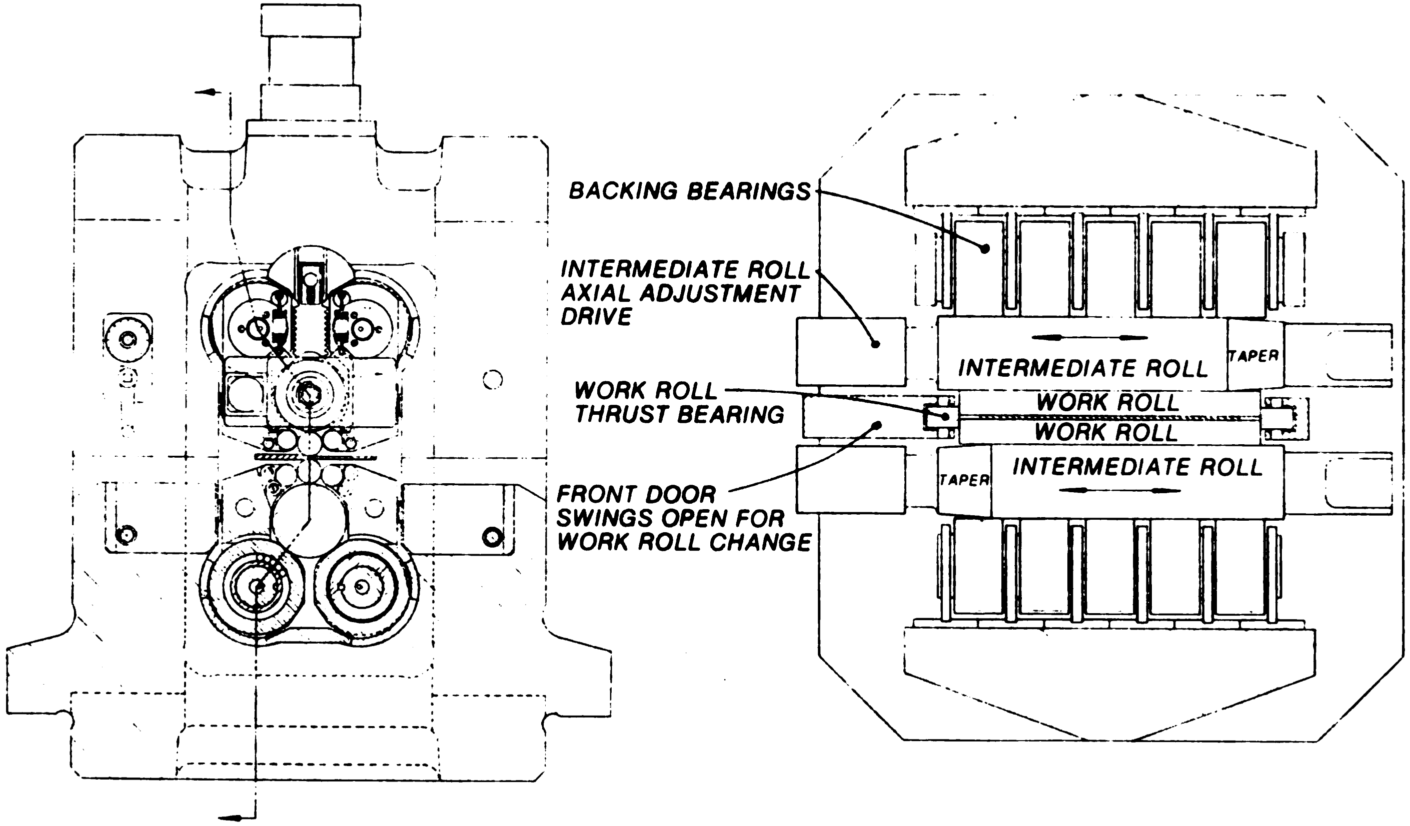
TABLE 4-13

MANUFACTURERS WITH SENDZIMIR MILLS CAPABLE OF PRODUCING WIDE THIN GAUGE SHEETS OF LOW CARBON STEEL

MANUFACTURER	LOCATION	MILL TYPE	SHEET WIDTH MM (IN)	MINIMUM SHEET THICKNESS MM (IN)
NOWA HUTTA	POLAND	ZR-21MB 55	140 (55)	0.15 (0.006)
PHOENIX WORKS	BELGIUM	ZR-22 50	127 (50)	0.20 (0.008)
NORSK BLICK	NORWAY	ZR-22 50	127 (50)	0.07 (0.003)
HOKATA KOHAN	JAPAN	ZR-22B 50	127 (50)	0.10 (0.004)
ACERINOX SA	SPAIN	ZR-22B 50	127 (50)	0.20 (0.008)

SOURCE : MR. F. KROWCHENKO, T. SENDZIMIR INC., WATERBURY, CT.
PERSONAL COMMUNICATION JUNE 13, 1980 (Reference 4-22)

FIGURE 4-5



Z-HIGH COLD ROLLING MILL

ZR-40 SERIES

Source: Reference 4-20

Based on the above, it is believed that steel producers could offer sheet steel 0.2 mm (0.008 in.) thick or less, in widths of at least 48 in. (122 cm), and possibly wider, that would be suitable for facings of metal plastic laminates, without having to make significant capital investments. By proper modification of sheet tension, lubricant characteristics and mill speed, operators of modern 54 in. wide, 4 high, 5 stand cold rolling lines now producing tin mill products should be able to roll steel sheets as wide as 48 in. in thicknesses of 0.006 in. to 0.008 in. (0.14 mm to 0.20 mm). Rolling of wider sheets to these gauges would require modification of wider rolling mills normally used to produce thicker gauge steel. A number of approaches could be used which could include an additional stand, which might be costly, the use of a Z-high mill (ZR 60 series) insert to retrofit an existing 4 high mill and allow the production of thinner gauges, or the simultaneous rolling of two sheets as suggested by Stone. Thus by starting with two thicknesses of hot band, nominally 2 mm (0.060 in.) each thick, 2 x 2 mm = 4 mm initial thickness), the mill could roll down to a double thickness of 0.40 mm (0.016 in.) or even less, which would produce to sheets each having a final gauge of 0.20 mm (0.008 in.), since steel sheets, 0.40 mm (0.016 in.) thick, are currently rolled in widths of up to 60 in., this might be a relatively simple method of producing 60 in. wide sheets of half this thickness. Further research would be needed to determine if it were practical to operate off two uncoilers, and to "double" the two strips as they entered the first stand, followed by a similar "undoubling" operation out of the last stand, in conjunction with dual rolls. There might be problems with cold welding of the two sheets which might require the possible use of a separation barrier, possibly a polymer film, between the bands being rolled (4-24). The fact that only one side of the sheet would have a bright finish would be of no concern in terms of its use as laminate facings. In fact, having a matte finish might improve facing-core bonding.

In terms of annealing practice, the concerns of the steel producers are directed principally towards the problems that would arise in the continuous annealing of very thin gauge sheet steel. Productivity in a continuous annealing oven might be hampered by frequent breakage of very thin sheets. Box annealing of thin sheets with proper supports should not present such problems.

Similar arguments also apply to the manufacture of thinner, wider aluminum sheets. Commercial practice in this industry has already established that certain alloys can be made in gauges thinner than required for laminates in widths that would satisfy most automotive requirements. It would be necessary to adapt and extend this technology to other alloys that would be of interest.

For these technical changes to be implemented, the sheet metal producers would have to be able to justify the risks entailed in modifying their current operations and adding new equipment in terms of their expected commercial rewards.

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5.0 FABRICATION CONSTRAINTS ON USE OF METAL PLASTIC LAMINATES

5.1 INTRODUCTION

In addition to the various design considerations discussed in the previous sections, there are a number of fabrication constraints which will restrain the use of metal-plastic laminates for certain automotive applications. These include:

a) Forming characteristics

b) Joining and fastening considerations

c) Stability in paint bake ovens

d) Compatibility with current methods of mechanical repair of fabricating damage

5.2 FORMABILITY

One of the principal advantages proclaimed for metal-plastic laminates is that components can be formed from laminate sheet by the same methods and equipment currently used to make the equivalent steel components. The forming characteristics of laminates, however, are not quite the same as those of steel, and vary with the properties and thickness of the face sheet, the total laminate thickness (i.e., the core volume ratio) and to a secondary degree, with the characteristics of the core.

5.2.1 Steel Faced Laminates

A series of simulative tests were performed by DiCello (5-1) to characterize the general formability of steel-polypropylene laminates. Some of these results are presented in Table 5-1. These tests were all performed at ambient. As can be seen from this Table, the forming characteristics of a laminate are principally established by the forming characteristics of the face sheets. Because the face sheets are thinner than a steel sheet of equivalent stiffness to the laminate, they do not have as much stretching capacity. As a result, a laminate is not as formable as the steel sheet of equivalent stiffness. However, DiCello also reported that a 1.0 mm steel—polypropylene laminate is more formable (i.e., has more stretchability) than an 0.86 mm thick aluminum allow 5182-0 which has an FLDo of 23 percent.

It was also observed that the stretchability of a laminate was greater than the stretchability of the face sheets from which the laminate is made. As noted in Table 5-1, the value of FLDo for a 1.0 mm laminate made with 0.2 mm face sheets is 33 percent, while the value of FLDo for the face sheet material alone is 28 percent. This also applies for thicker laminates. An 8.3 mm

TABLE 5-1: FORMABILITY OF STEEL - POLYPROPYLENE LAMINATES RELATIVE TO STEEL

	BODY SHEET			HEAVY GAUGE SHEET		
MATERIAL	STEEL	EQUIVALENT LAMINATE		STEEL	EQUIVALENT LAMINATE	
		LAMINATE	FACING		LAMINATE	FACING
THICKNESS, MM	0.76	1.02	0.20	1.57	1.73	0.34
HOLE EXPANSION TESTS						
PERCENT INCREASE IN DIAMETER	78	32	35	86	39	47
PERCENT TOTAL ELONGATION	43	35	33	46	37	35
CUP DRAWING TEST						
LIMITING DRAW RATIO(LDR)	2.4	1.8	2.2	2.4	1.8	2.2
FORMING LIMIT DIAGRAM						
FLD, PERCENT	45*	33	28		30	
SPRINGBACK, °	13	14				

* 0.90 MM THICK STEEL FOR FLD

SOURCES: J.A. DI CELLO, SAE PAPER 800078 (Reference 5-1)

S.P. Keeler, "Sheet Metal Forming in the 80's", Metal Progress, 118 (2), 25, July 1980 (Reference 5-3).

thick laminate made with 0.9 mm face sheets, has a FLDo value of 47 percent, which is slightly higher than the value of 45 percent reported for 0.9 mm steel on Table 5-1.

Somewhat different results were reported by Yutori, et al. (5-2), who found that drawability of a sandwich with 0.6 mm steel face sheets separated by an 0.05 thick resin core is superior to that of the unsupported 0.6 mm steel, but that increasing the thickness of the resin layer to 0.2 mm resulted in poorer drawing characteristics than those of the face sheet.

In explanation of this behavior, it is proposed (5-3) that the site of incipient localized necking or thinning statistically differs for each skin of a laminate, so that one skin becomes a strong "reinforced backing" at the necking site. Deformation continues until a common necking site develops.

Other tests performed by DiCello suggest that the blanking and trimming characteristics of laminates, as well as their spring-back characteristics, are similar enough to those of steel of comparable thickness that normal clearances for a given steel thickness are satisfactory clearances for a laminate.

One of the great advantages of focusing on steel faced laminates with less than a seventy percent core volume ratio is that these laminates are only ten to twenty percent thicker than the steel sheet of equivalent performance (i.e., stiffness). As a result, the stamping dies that would be used to make a part with such a laminate would be very similar to those now used to form the equivalent steel part. In some instances, where it is desired to make test parts from laminate stock, existing production dies could be used without modification for these trial runs.

Some further constraints are imposed by the greater tendency of laminates to wrinkle under deep draws than a steel sheet (5-1, 5-2). A laminate has a greater tendency to wrinkle because it can be difficult to support both the inner and outer skins during a forming operation. For example, as a laminate blank is drawn into a die cavity, the outside skin will be supported by the die radius and will not wrinkle. The inside skin will be in the area between the blank holder and the punch. In this unsupported region, if a critical buckling stress is achieved, the inside skin will wrinkle since the soft core will not be able to constrain its movement. This consideration will require careful tool design and blank development for laminates to be used in instances where this problem can arise.

5.2.2 Aluminum Faced Laminates

The early work by Pohl and Spencer (5-4) indicated that aluminum faced-polyethylene laminates could be readily post formed at temperatures which soften the core material and allow independent motion of the skins. They developed a process in which a laminate blank is heated only in the section to be deformed in order to soften or melt the core material while the edges are maintained cool and solid. When forming pressure is applied to the laminate blank, the soft but incompressible core material transmits pressure evenly from the upper to lower skin. This allows sliding of the skins relative to each other, distributing the strain to the area adjacent to being deformed and introducing strain relief. Because of this phenomenon, Pohl and Spencer were able to deep draw laminates even with skins of low ductility aluminum alloys such as 2024-T3 and 7075 T6.

More recently, McKenna, et al. (5-5) similarly found that optimum forming of aluminum-nylon occurred at temperatures above ambient, in the range of 66-107°C (150-225°F), as indicated by the test results presented in Table 5-2. It is to be noted that the stretch ratios achieved with the aluminum-nylon laminates are in the same range as those achieved by traditional auto-body panel materials. While the stretch forming ratio of a laminate is strongly dependent on the forming characteristics of the face sheet alloy, it was noted, as indicated by the results presented in Table 5-3, that a laminate was capable of sustaining significantly greater strain than its unsupported face sheets.

These results are similar to the ones obtained by Pohl and Spencer with aluminum-polyethylene sandwiches and by DiCello (5-1) with steel-polypropylene sandwiches. McKenna, et al., also noted that the springback characteristics of aluminum-nylon laminates formed at elevated temperatures were superior to that of aluminum-nylon laminates formed at room temperature.

Severely formed parts have been fabricated on commercial presses with aluminum-nylon laminates. These include a truck-body ball corner that was formed on a drop hammer, and an aircraft bracket on a hydropress. In both instances, the blanks were preheated to a temperature range of 150-225°F (66-107°C).

Aluminum-faced laminates that are functionally equivalent to sheet steel in terms of stiffness, will be typically 50 to more than 100 percent thicker than the steel. This can present an obstacle to the fabrication of test parts with tooling designed for steel components, which may not arise with steel faced laminates that are just slightly thicker than the steel baseline material. The large gap thickness required to fabricate an aluminum faced laminate makes it unlikely that a die designed to stamp steel parts can be used without modification with the aluminum laminate. As a result, special dies are more likely to be required for an aluminum laminate component development program than for a steel laminate development program. Once dedicated tooling is stipulated, this relative disadvantage disappears.

5.3 JOINING AND FASTENING

The joining and fastening of metal-plastic laminate

TABLE 5-2: FORMABILITY OF ALUMINUM - NYLON LAMINATES

MATERIAL	THICKNESS	FORMING TEMPERATURE	OLSON CUP STRETCH FORMING RATIO	SPRINGBACK OLSON CUP SAMPLES
	MM	^oC	PERCENT	PERCENT
AUTO HOOD STEEL	0.84	23	38	5
ALUMINUM (2036-T4)	1.02	23	32	9
1100-0 ALUMINUM-NYLON	1.5*	23	41	
		76	46	
6061-0 ALUMINUM-NYLON	1.5*	23	39	**
		76	41	
		100	40	7
6061-T4 ALUMINUM/NYLON	1.5*	23	28	**
		76	31	8

* Assumed value implied from the paper since the actual value of thickness of test samples was not explicitly reported by the authors.

** In text of paper, authors report that springback is much greater for laminates when they are formed at room temperature

SOURCE : L.W. MC KENNA ET AL, SAE PAPER 800079 (Reference 5-5)

TABLE 5-3

STRETCH FORMING RATIOS AT FAILURE FOR ALUMINUM-NYLON LAMINATES AND ALUMINUM SKINS

FACE SHEET ALUMINUM ALLOY	THICKNESS mm(m)	METAL SKIN ONLY	LAMINATE*
1100-0	0.13 (.0052)	.32	.46
6061-0	0.16 (.0062)	.26	.41
5052-0	0.13 (.0052)	.24	.37
5052-"H38"	0.13 (.0052)	.22	.29
6061-"T4"	0.16 (.0062)	.22	.31

* Data normalized to a laminate thickness of 1.5 mm (0.060 in)

Source: L.W. McKenna et al., SAE Paper 800079 (Reference 5-5).

components to each other, or to components fabricated from other materials, is complicated by the heterogeneity of the laminates and the thickness of the skins. In the attachment of a piece of solid sheet, the stress is supported through the total thickness of the sheet. In attaching to either side of a metal laminate, only the contacting face sheet will be the load bearing member. The effectiveness of attachment to one side of a metal plastic laminate will be limited by the strength of the face sheet and/or of the skin-core bond. This becomes an important consideration with laminates of interest which typically will have skins less than 0.25 mm (0.010 in.) thick. Attachment to both sides of a laminate would provide greater strength, but is likely to be more costly and may not always be feasible.

Of the various possible methods of joining that can be considered, namely adhesive bonding, welding, or mechanical fastening, structural adhesive bonding appears to be the most satisfactory method of joining metal-plastic laminate components. Their major drawbacks are the time and temperature required for cure which would require the use of jigging or other short-term tacking methods in conjunction with the structural adhesives. Conventional welding techniques that are the current standard method of joining sheet metal parts in the automobile industry do not appear suited to joining metal-plastic laminates. However, specialized welding methods that have been developed and used with pre-coated steels should be applicable in particular situations, especially with laminates that have relatively thick face sheets, greater than 0.6 mm (0.025 in) in thickness. The potential for creep of the polymer core under normal loads to the laminate, and the resulting torque loss, severely limit the use of mechanical fastening as a method of attachment to non-critical applications where the applied stresses are small.

5.3.1 Structural Adhesive Bonding

During the past thirty years, structural adhesives have played a key role in the development of lighter, lower cost, more reliable military and aerospace hardware, and in the success of the passenger jet industry. But the adhesives which have been developed for the air frame and aerospace industries, as well as the adhesive bonding processes themselves, have found limited use in the automotive industry. The assembly line conditions encountered in the automotive industry place several requirements on candidate structural adhesives that do not necessarily exist in the aerospace industry.

The general requirements for automotive manufacture are:

- Simple means of application
- Tolerance of, and forgiveness for, minimal surface preparation

- Ability to bond to varied metal and plastic surfaces
- Rapid development of initial bond strength sufficient to hold the assembly together
- Development of high ultimate bond strength (of the order of 3000-6000 psi (21-41 MPA) in shear) within the constraints of the assembly/manufacturing operation
- Low order of toxicity
- Reasonable cost

Structural adhesive bonding has been finding more extensive use in the automotive industry in the past decades. The bonding of hoods and deck lids with a heat curing, vinyl plastisol was introduced in 1960, and is now a common assembly practice. By using a mastic adhesive, it was possible to obtain lighter, stronger assemblies, and to eliminate the flutter and rattle that occurred with these components at road speeds. Manufacturing complexity was also reduced by eliminating sprayed on asphalt sound deadeners and asphalt impregnated anti-rattle pads (5-6). Epoxy adhesives have been used in a varied assortment of automotive applications (5-7). These include the use of a one component epoxide that cures at 100° - 120°C to bond the lens to the reflector of halogen quartz head lamps, conducive epoxies for a variety of passenger car electronic devices, and a one component epoxy adhesive in the rivet-bonding of school bus exterior panels to the support frame. The rivet bonding process consists of applying a structural adhesive between the overlap edges of a sheet steel joint before holes are drilled, and rivets or other mechanical fasteners are then inserted. Rivet bonding results in stronger, more stable joints than can be achieved by either mechanical fastening or adhesive bonding alone. It also eliminates the need for fixturing or curing equipment since the mechanical fasteners hold the joints together until the adhesive cures when the assembly passes through a paint bake oven. Within the last several years, so-called "second generation acrylic adhesives" have been developed for bonding a wide variety of metals without preparing the adhering surfaces. Using these adhesives, even oily, poorly mated, mill finished components can be bonded quickly and efficiently at room temperature (5-8, 5-9). To demonstrate their use, such second generation adhesives have been used to bond an automobile radiator to support brackets or to bond a filler neck to the body of a radiator (5-8).

A number of techniques have been developed within the past few years to accelerate the cure of adhesives that focus energy principally in the general area to be bonded. These include UV, IR, microwave, dielectric, inductive, ultrasonic and electron beam bombardment (5-9). An interesting example of magnetic induction heating of an adhesive is the Tenabond System that was commercialized by Illinois Tool Works Inc. (ITW). With the Tenabond System, which includes a 10 kHz generator, a temperature indicator/control loop, and fixturing equipment, thermal energy is focused on a patch of epoxy adhesive and allows unusual material combinations to be bonded in cycle times of less than one minute. The Tenabond System has been used to bond support bolts to glass windows for Chrysler passenger vehicles, and plastic molding clips to finished painted doors for the 1978 Ford Granada (5-10).

All the above techniques should be applicable to the joining of metal-plastic laminate components. The great advantage of adhesive bonding over other fastening techniques is that adhesive joints usually entail relatively large contact areas in comparison to other fastening techniques, so that one deals with distributed loads that are compatible with the strength capability of the thin laminate skin.

The overall rate of acceptance of adhesive bonding by the automobile industry may be the pacing factor in the rate of introduction of metal-plastic laminate by the industry, particularly for thin laminates where other fastening/joining methods do not appear to be satisfactory.

5.3.2 Welding of Metal-Plastic Laminates

A number of welding methods have been developed for organic coated steel which can also be used with sandwich laminates with face sheets of sufficient thickness (5-11 to 5-18). The most widely used assembly method for sheet steel is resistance welding. Direct resistance welding will not work with precoated steels or with laminates because the plastic layer is an excellent electrical insulator, so that no current will pass under direct spot welding conditions. A laminate can be welded if an initial shunt path is used, as outlined in Figure 5-1. A third, starting electrode is clamped to the surface of the laminate near one of the starting electrodes. Initial current flows through the welding electrode, one face sheet, and the third electrode. The heat generated by this operation will soften the polymer layer sufficiently to allow the welding electrodes to press the two skins of the laminate together so that the current will then pass directly across the path between the primary electrodes. Sufficient pressure must be maintained to assure that the two metal sheets come into contact and the polymer is displaced. Subsequent welds made in the vicinity will not require the starting electrode.

Projection welding, which has become commonplace with coated steel, can also be used with sandwich laminates, as shown in Figure 5-2. Although conventional domed projections can be used, with laminates, it is preferable to use annular type projections which give a large diameter weld, but which result in minimum sheet indentation. To prevent heating and distortion of the laminate, cycle times have to be short and water cooling may be required. Brackets, studs, weld nuts, and other types of projections can be direct projection welded to both skins of a laminate

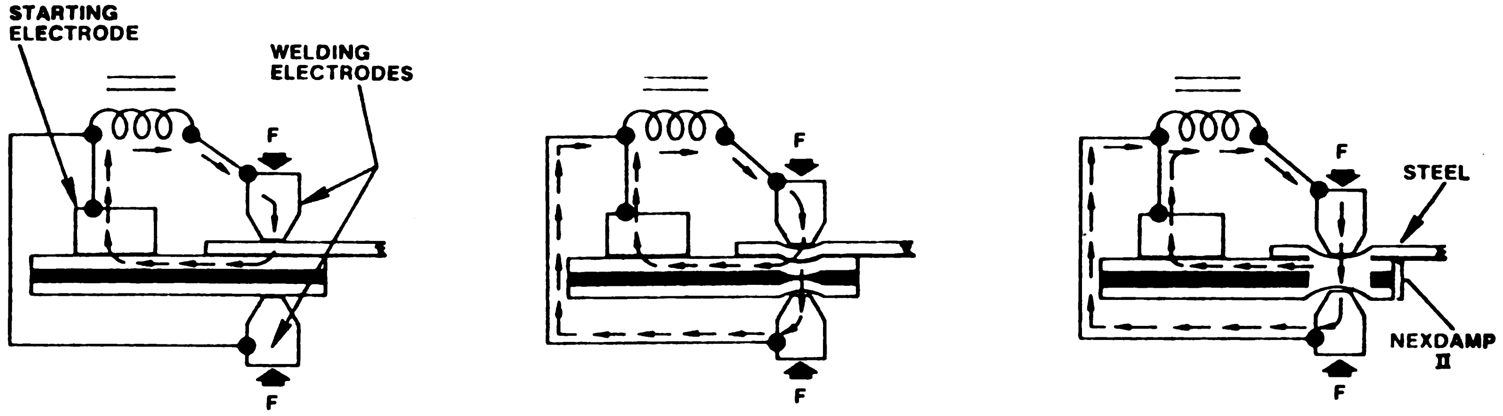


FIGURE 1 — MAKING THE FIRST WELD WITH STARTING ELECTRODE

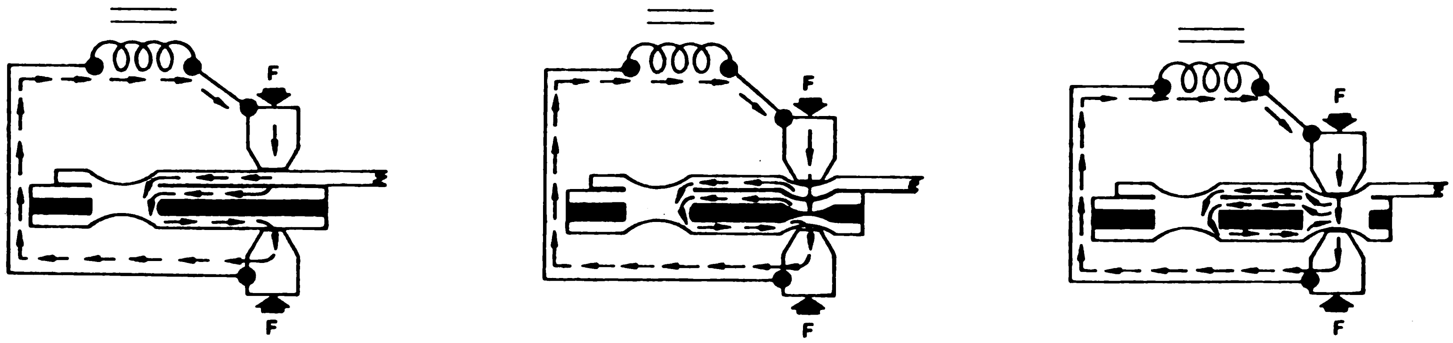
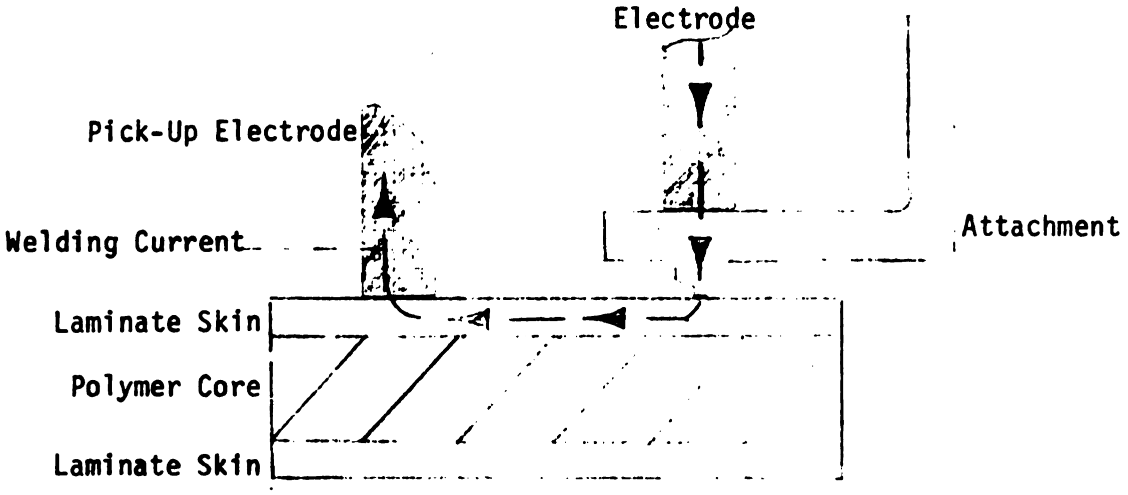


FIGURE 2 — MAKING SUBSEQUENT WELDS

Source: Reference 5-12

FIGURE 5-1 SHUNT WELDING PROCEDURE FOR THE SPOT WELDING OF METAL-PLASTIC SANDWICH LAMINATES



SOURCE : Reference 5-14

FIGURE 5-2 DIAGRAM OF USE OF PROJECTION WELDING WITH LAMINATES by using the starting electrode method outlined in Figure 5-1.

An alternative method to resistance welding is capacitor discharge stud welding which has been used for attaching studs to the reverse side of all types of organic coated steel. Based on the principle of discharging a large bank of capacitors through a small projection raised on the end of a stud, the welding time is extremely short. With stud welding, it has been possible to weld an attachment to the back of a vinyl coated steel sheet 0.025 in. (0.6 mm) thick without marring the vinyl surface (5-12).

Electron beam welding which has been successfully used to bond temperature sensitive electronic components may be yet another method of fastening metal plastic laminates.

Because of the higher temperatures involved with normal gas or arc welding, these methods of welding should not be used with metal-plastic sandwich laminates. At the temperatures generated, the polymer core decomposes, resulting in the generation of noxious fumes and contamination of the weld.

The constraint on the use of any of the above welding methods with the metal-plastic laminates of interest to the study is the thickness and the strength of the metal face sheets. It has been demonstrated that the presence of a non-conductive plastic layer is not a barrier to the welding of precoated sheet or thick sandwich structures, i.e., with metal sheets at least 0.6 mm thick, and usually 1.0 mm thick or more. Further work is required to demonstrate that these methods are workable with the 0.15 mm to 0.2 mm thick sheets that would be used with laminates designed for auto body panels. With these thin sheets, there is a question that even if a suitable weld could be formed, the face sheet supporting weld may not have sufficient strength to support the assembly.

5.3.3 Mechanical Fastening

Most of the traditional methods of mechanical fastening for sheet steel can be used with metal-plastic laminates. These include threaded fasteners, rivets, staples, stakes, spring fasteners, and lockseaming among other methods. The usual care in materials selection must be made to prevent inter-metallic corrosion. The major disadvantage of mechanical fasteners derives from the tendency of the plastic core of the laminate to creep under a normal load, especially at high loads and elevated temperatures relative to the melting or softening point of the plastic (5-1). Mechanical fasteners may also be undesirable from an appearance point of view.

Mechanical fastening may be required as an adjunct technique to adhesive bonding in order to hold the assembly together until the adhesive cures. Lockseaming may be particularly useful in this context in terms of external appearance. It also offers an additional advantage of completely masking the sheared edge of the laminate in the convolutions of the joint.

5.4 STABILITY IN PAINT BAKE OVENS

One of the touted advantages of metal-plastic laminates is that the metal skins can be painted in the same manner as automotive sheet steel. Thus, in principle, metal-plastic laminates are viable candidates for appearance parts which require a "Class A" finish. In practice, problems have been encountered in the painting of formed metal-plastic laminate components parts because of severe mechanical distortion of these parts after passage through the paintbake ovens.

Figure 5-3 is a representation of the process operations characteristic of automotive assembly plant paint shops. It is an amalgam of information obtained from the technical literature and discussions with representatives of the automotive manufacturers (5-19 to 5-25). The temperatures indicated as Tmax in Figure 5-3 are representative of the air temperatures in the various bake cycles. Tmax is approximately 30°C (54°F) higher than the typical equilibrium temperature of a part passing through the bake oven. Typical residence times are of the order of 10 min. to 30 min. However, parts may be kept in an oven for a longer period of time when the assembly line is stopped for any reason. Under these circumstances, the temperature of a part will rise and approach the oven air temperature, Tmax.

Any laminate part has to be able to survive half-hour exposure to temperatures of either 400°F (204°C) or 350°F (176°C) depending on whether an electrocoat prime is used or not, with the higher temperature level being characteristic of most components on the body-in-white.

Distortion of laminate parts is primarily a function of the melting or softening temperature of the polymer relative to the operating temperature of the paint bake oven. The differences in the coefficients of thermal expansion of the metal skins and the polymer core may be a secondary contributory factor. Thermal properties of various core polymers and metal skins are given in Table 5-4. As indicated in Figure 5-4, all the polyolefins have softening or melting temperatures below the maximum exposure temperatures of either the spray prime bake oven or of the "E-coat" bake oven. Of the polymers currently mentioned as candidates for metal-plastic laminates, only nylon 6-6 has a melting temperature that is higher, and by a significant margin, than the maximum exposure temperature of the "E-coat" bake oven. It is to be noted that thermoplastic polyesters are a class of commodity polymers (i.e. polymers selling for less than $1/lb) that exhibit a high degree of thermal resistance. Both polyethylene terephthalate (PET) and polybutylene terephthalate (PET) have melting points that are significantly higher than 400°F (204°C), and should be considered as candidate core materials.

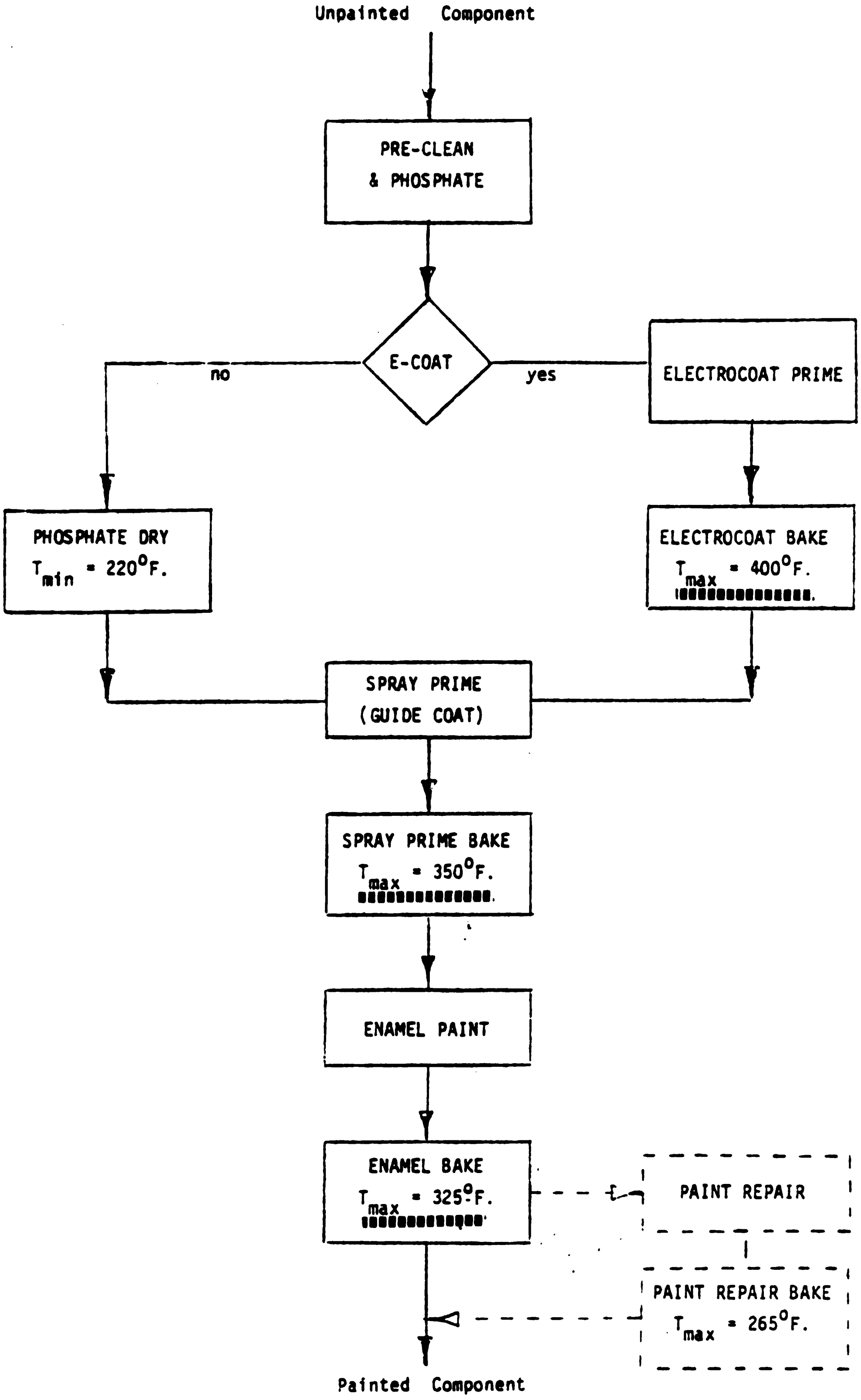


FIGURE 5-3 REPRESENTATIVE TEMPERATURE LEVELS OF AUTOMOTIVE PAINT BAKES

TABLE 5-4 THERMAL PROPERTIES OF CORE POLYMERS AND METAL SKINS

MATERIAL	MELTING TEMPERATURE ^{o}F	DEFLECTION TEMPERATURE UNDER FLEXURAL LOAD (66 PSI) ^{o}F	COEFFICIENT OF LINEAR EXPANSION CM/CM-^{o}C X 10^6
POLYETHYLENE, LD	203 - 266	100-121	90 - 105
POLYETHYLENE, HD	248 - 284	140-190	110 - 130
POLYPROPYLENE	334	225-250	81 - 100
POLYPROPYLENE, 40% TALC FILLED	316 - 334	265-290	55 - 80
NYLON 6-6	509	474	80
THERMOPLASTIC POLYESTER (PBT)*	450 - 513	240-375	60 - 95
THERMOPLASTIC POLYESTER (PET)*	473		65
STEEL			12
ALUMINUM			24

* NOT USED IN METAL-PLASTIC LAMINATES CURRENTLY UNDER DEVELOPMENT

SOURCES: <u>PLASTICS</u> - MODERN PLASTICS ENCYCLOPEDIA, VOL 56, 1979-1980

<u>METALS</u> - HANDBOOK OF PHYSICS AND CHEMISTRY, 33RD ED., 1951-1952

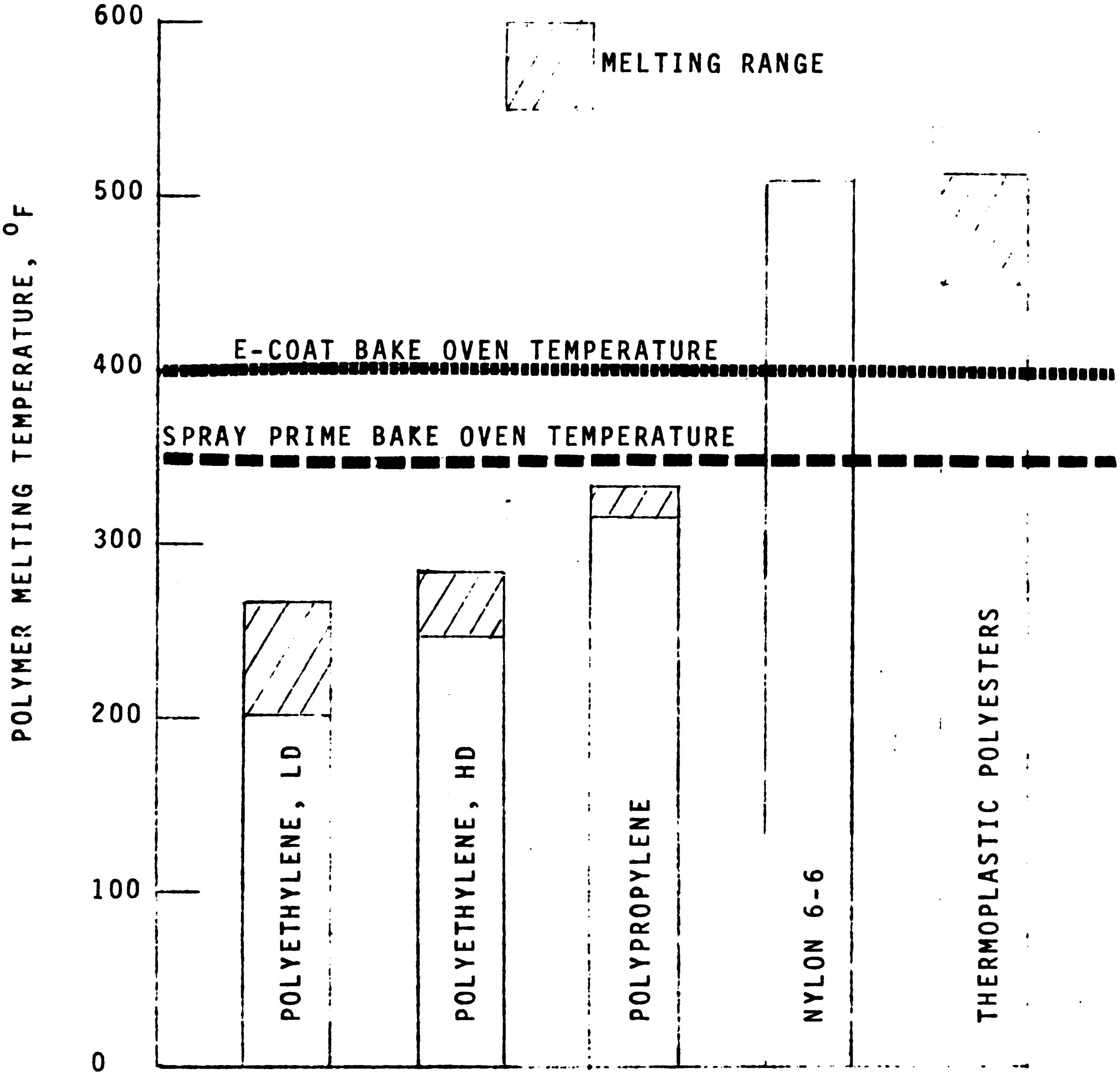


FIGURE 5-4. POLYMER CORE STABILITY IN PAINT BAKE OVENS

It is to be noted further that the coefficients of thermal linear expansion of the polymers listed in Table 5-4 are from three to ten times as large as the coefficients of thermal linear expansion of steel or aluminum.

According to preliminary tests performed to date (June 1980) at Ford Motor Company (5-25), none of the metal-plastic laminate components examined survived passage through the E-coat bake. These tests were performed on candidate test panels prepared by material suppliers. Only aluminum-nylon 6-6 laminates survived the spray prime bake. The maximum exposure temperature for steel-polypropylene laminates was 300°F (149°C) or less, depending on the formulation of the core.

These results can best be explained in terms of the relaxation of the internal stresses induced by the cold forming of the laminate component. Since the stress patterns for each face sheet are different, when the polymer becomes too soft to support shear, relative motion of one face sheet with regards to the other will follow.

Thermal distortion may occur even if the core does not melt if some form of stress relief or distribution occurs at the paint bake temperatures because of the differences in the coefficients of thermal expansion of the cores and the skins. If no stress redistribution occurred in the paint bake cycle, there would be no permanent distrotion in part, since any distortion that resulted from heating a part from room temperature to the paint oven temperature would disappear again as the part was brought back to ambient. However, if there is some stress redistribution during the bake cycle, symmetry of distortion with respect to increasing and lowering temperatures may no longer exist.

Based on the data presented in Figure 5-4, the Ford results are not unexpected, except for the failure of the aluminum-nylon laminate part to survive passage through the E-coat cycle. These results are not in agreement with the claims of the supplier (Monsanto Corp.) and are the results presented in Table 4-4.

These results are cause for concern in terms of using any metal-plastic laminate for components that must have an electrocoat prime coat. Further investigation of metal-plastic laminates that have thermally stable cores is required if these laminates are ever to be considered as viable candidates for any appearance part or supporting inner panel. Candidate laminates, in addition to Monsanto's aluminum-nylon 6-6 laminates, should include steel-nylon 6-6 laminate which may have less tendency to distort because of the higher stiffness of steel (but which may be counteracted by the fact that steel has a lower coefficient of thermal expansion than aluminum), and thermo-plastic polyester core laminates. Consideration should also be given to mineral filled nylon 6-6 or polyesters because the coefficients of thermal expansion of these filled polymers are much lower than those of the unfilled polymers, approaching the coefficient of linear expansion of aluminum in absolute value. Use of filled polymers would result in a denser core, and thus a loss in weight savings, but would lower the cost per unit volume of the core.

At the moment, polyolefin cored laminates can only be considered as candidate materials for unpainted parts.

Automotive painting practice is currently undergoing review and may be significantly modified in the near future because of increasing costs of energy and the need to meet more stringent environmental constraints. Within the constraints of costs and finish quality the automobile manufacturers, and their paint suppliers, are trying to develop primers and finishes that cure at lower temperatures than those characteristic of current manufacturing practice. The critical problem in terms of laminates is the E-coat bake temperature. There is on-going effort to reduce the cure temperature of E-coat primers (5-25) but it is doubtful, even under the best of circumstances, that cure temperatures (over air temperatures) of much less than 150°C (300°F) for these primers will be ever achieved. Water borne spray primers, water base enamels, polyester/amino-resin cross linked enamels, and two pack urethane enamels (5-19, 5-20) are characteristic development activities directed at reducing the cure temperature of other automotive painting operations. There is a possibility that, aside from the electrocoat bake, various automotive paint bake ovens could be operating at temperatures of 275°F (135°C) or less. This would allow one to project that polyolefin core laminates could be candidates, one day, for all parts except those passing through the E-coat paint bake oven. For polyolefin cored laminates to be used for those components that are now electrocoated, the skins would have to be primed before lamination. Even if the automotive paint suppliers could develop a flexible primer that would adhere to the metal substrate during deep draw and withstand in-plant handling, it is doubtful that the automotive manufacturers would abandon the "electrocoat dip" of the body-in-white, since one of the great advantages of electrophoretic deposition is the ability to apply primer in otherwise inaccessible crevices in the assembled unit, and which are the likely places for the initiation of corrosion.

5.5 MECHANICAL REPAIR OF FABRICATING DAMAGE

Metal finishing is a repair operation performed at the fabricating plant and/or the assembly plant to remove objectionable defects in sheet metal parts prior to painting. While rigid quality control standards can minimize the presence of dents, dings, scratches and burrs, such defects will never be completely eliminated under high volume production conditions. In addition, joints between major body components must be masked.

The current practice is constrained by the pace of assembly line operations. Dents are pushed or hammered out from behind where feasible, or filled with a lead alloy. At present, lead solders are also used to fill indentations and joints between steel body panels. Dings and deep scratches are filed to ensure flatness relative to surrounding areas. File marks, surface scratches and other surface irregularities are then removed with coated abrasive discs mounted on air driven grinders. Typically, fiber backed resin bonded aluminum oxide discs are used in grit sizes ranging from 50 to 120 (5-26).

Metal-plastic laminates are not compatible with current finishing practice. The use of lead fillers will cause local melting of any of the polymer cores being considered, and is likely to result in local distortion. The filing and grinding methods now used to obtain smooth surfaces would remove a significant fraction, or possibly all, of the external metal skin, thereby greatly weakening the laminate. Removing 0.1 mm (0.004 in.) of surface metal from a 0.8 mm (0.032 in.) thick steel sheet reduces the thickness by less than 15 percent, whereas removing 0.1 mm of surface metal from a 0.2 mm thick face sheet removes 50 percent of the metal.

Changes in finishing practice are required if metal-plastic laminates are to be used in appearance parts even if the obstacles presented by the high temperature of the primer bake ovens are overcome. The automobile industry has searched actively for years to find a replacement for lead solder for reasons of weight savings, employee safety and costs (5-7, 5-25, 5-26). During this period, plastisols were developed for filling those roof joints which are covered with vinyl fabric. Epoxies have been used to a limited extent for filling small, low visibility joints below doors or around head lamps on certain passenger cars. In all cases, the plastisol or epoxy was cured in existing bake ovens.

Although the major U.S. passenger car manufacturers have not yet converted from lead to epoxy, the feasibility of using epoxy fillers on an assembly line has been demonstrated by Checker Company of Kalamazoo, MI. At Checker, dents and seams and filled by applying a one component epoxy to untreated and unprimed steel in the body-in-white, and then curing it by applying a direct flame, using the same hand-held gas torches previously used to melt lead. Following five years of limited production and field experience, Checker decided to eliminate lead solder completely and converted to epoxy filler with 1977 model year vehicles (5-7).

Removing of dings and scratches will be more difficult. It requires the development of more controllable, less abrasive polishing methods. More emphasis will have to be placed on filling rather than filing. While such modifications are inherently not difficult they may be finicky, and it may not be easy to incorporate them into an assembly line environment.

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6.0 REPAIRABILITY, SCRAPPAGE AND RECYCLING

This chapter addresses constraints that might be imposed on the automotive use of laminates by current methods of field repairing damaged body components, and by current methods of disposal and recycling of manufacturing scrap, and of junk cars.

6.1 FIELD REPAIR OF LAMINATES

Metal-plastic laminate parts should be repairable in standard body shops. There will be some differences in procedures as compared to those currently used with sheet steel components. Care will have to be taken if laminate parts are removed with a torch because of the flammability of the core. On the other hand, laminates will be easier to drill through and cut with a saw than steel sheet. Damaged laminate sections could be readily removed with a hacksaw or a portable power jigsaw. In the removal of dents and dings, not as much force will be required to straighten panels as is now used with steel. Joining of non-bolted parts will be by adhesive bonding rather than by welding. Plastic fillers and body putty would have to be used exclusively for filling joints and cracks. Greater care will have to be taken in the preparation and polishing of surfaces than is currently the norm with steel. The specific operational changes listed above are no different than those listed in Section 5.5 on in-plant repair of laminate parts. These issues are not considered to be major problems in terms of field repair because of the totally different environment in which these repairs are performed. The time pressures of the assembly line are not as pervasive in a field repair shop. Craftmanship and pride in personal endeavor can flourish in a small body shop. These elements allow for the extra bit of care which laminate repair will entail.

Painting of metal-plastic laminates in body shops will present no problems because of the low cure temperatures used with paints designed for the after-market.

The above discussion is based on actual experience. Marathon Electric Vehicle Company of Montreal, Canada is a specialty vehicle manufacturer that produces electric vans, of the type pictured in Figure 6-1, at the rate of approximately fifteen per month (6-1). This vehicle has a unique upper body construction, consisting of 4mm Alucobond^R aluminum polyethylene panels supported on an aluminum bird cage. By using this approach, Marathon feels it is able to produce a safe, lightweight vehicle with a minimum front end investment in tooling. Approximately 300 ft^2 ($\sim$38m^2) of Alucobond^R are used per vehicle. This material is used for all external surfaces, the doors, the dashboard, the load deck, the battery housing cover--essentially all the on-board potential sheet metal applications. The vehicle is designed so that none of the Alucobond^R components are formed in a stamping press. The only required tooling are a band saw and a roll

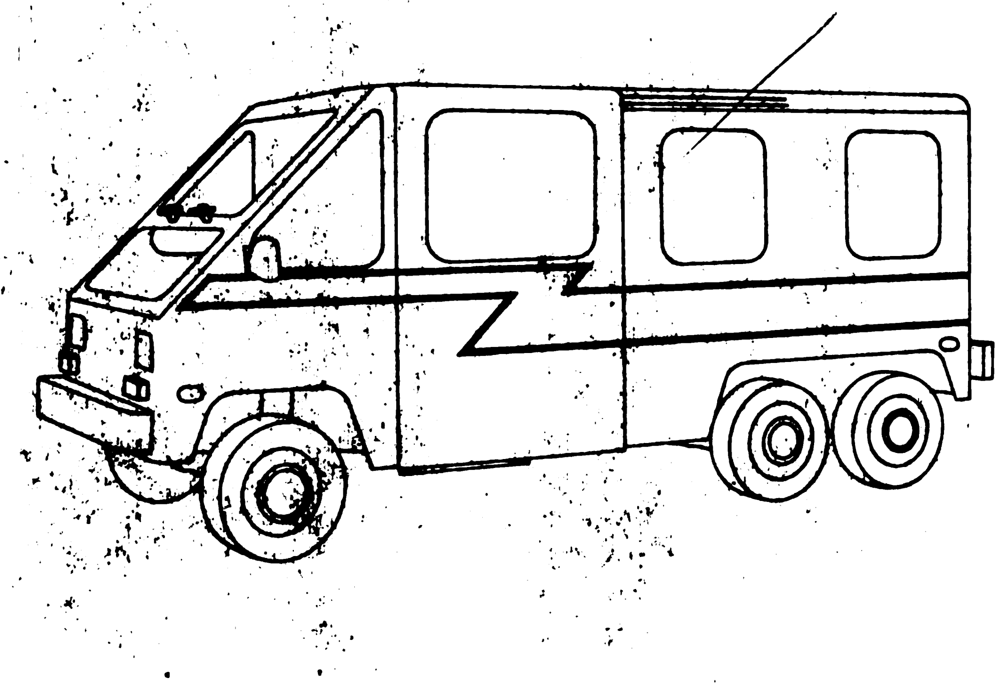


FIGURE 6-1. THE MARATHON C-360 ELECTRIC VAN - AN EXAMPLE OF EXTENSIVE USE OF METAL-PLASTIC LAMINATES ON AN AUTOMOTIVE VEHICLE

press. All components are either flat or have one degree of curvature. The vehicles are painted in an adjacent local body shop.

One of these vehicles was involved in a crash which damaged one of the rear quarter panels. The damage was repaired and repainted in the body shop without difficulty. This repaired vehicle was examined by the author, and the repair work appeared satisfactory.

The Marathon Electric Van is not a typical mass produced automobile. Furthermore, it uses a laminate that is much thicker than the laminates that would be used for sheet metal components in a mass production automobile. The weight per unit area of 4mm thick Alucobond^R is the same as 0.70 mm (0.028 in) thick steel. It is significantly stiffer than 0.8 mm sheet steel but offers little weight savings. The significance of the Marathon Electric van, in terms of this section of the study, is that the use of a metal-plastic laminate made it possible to build, assemble and finish an automotive vehicle in a body shop.

6.2 SCRAPPAGE AND RECYCLING

There are two aspects with regards to the issue of scrappage and recycling of any material used by the automobile industry. The first entails the disposal and economic value of the offal engendered in the manufacture of the vehicle. The second entails the disposition of a junk automobile, typically ten years later, after it is no longer useful as a mode of transportation. With proper reclamation, there is a closed cycle that ties the scrappage associated with one vehicle to the manufacture of a new vehicle, as outlined in Figure 6-2 (6-2). The extent to which the automotive materials cycle is closed is a function of the demand for processed obsolete scrap by mills and foundries. If there is a high demand, and a commensurate high price offered for the processed obsolete scrap, the materials cycle is effectively closed. If the demand is low, the price offered may not be sufficient to warrant the effort necessary to collect, prepare and ship the scrap. Under these circumstances, the materials cylce is broken, and the offal, or a deregistered automobile, becomes solid waste which has to be disposed of.

The driving force behind the reclamation of automobile hulks is the demand for ferrous scrap since iron and steel make up the bulk of the weight of an automobile. Because of a combination of recycling technology and steel melting methods in the 1960's, there was relatively little demand for either auto hulks or their derived products. This resulted in an accumulation of abandoned automobile hulks, which was a problem of national concern. With the widespread implementation of improved steel scrap preparation technology, the auto shredder, and improved steel scrap utilization technology, principally the electric furnace, the collection

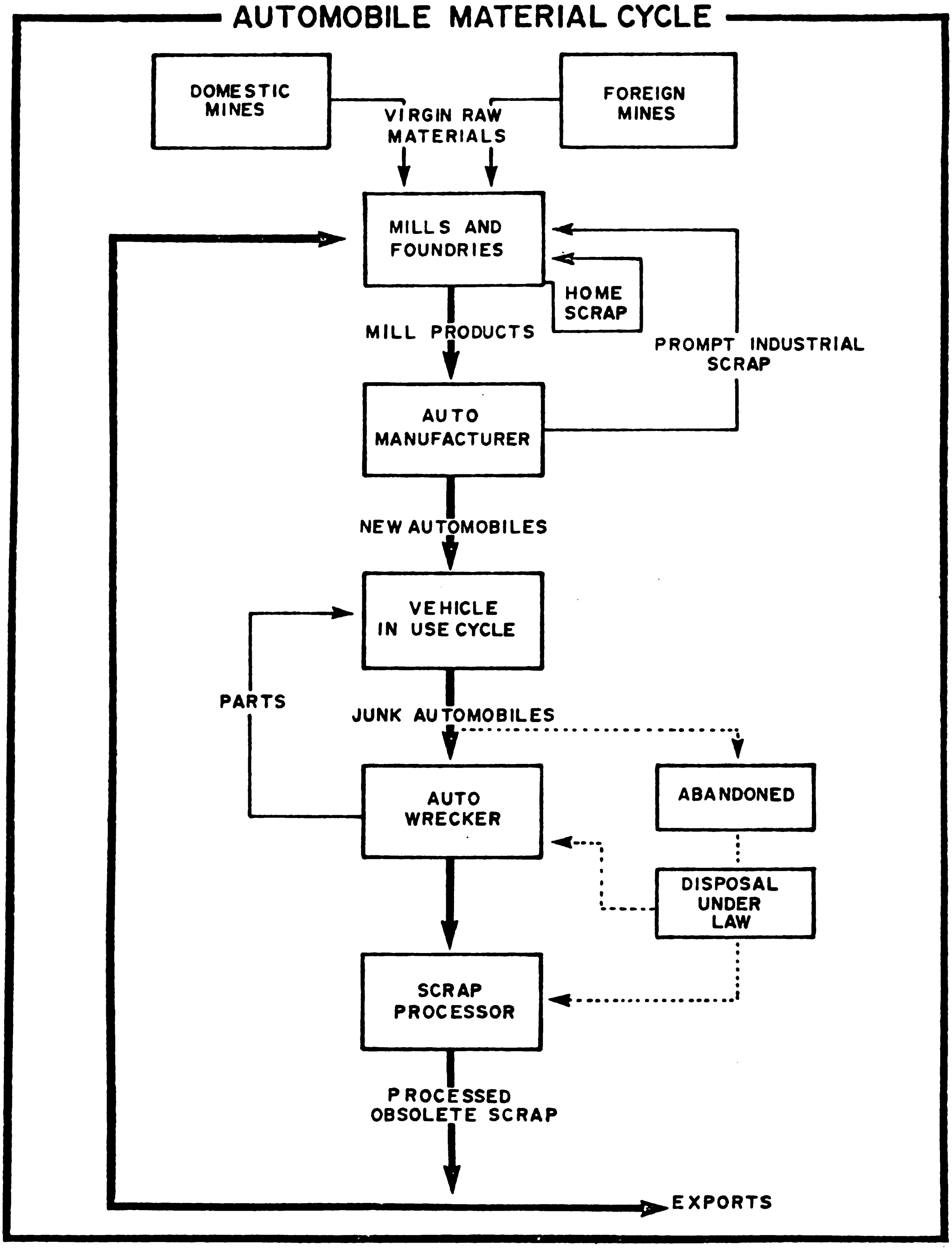


FIGURE 6-2 AUTOMOBILE MATERIAL CYCLE

of junk automobiles became a profitable enterprise, and the problem of abandoned auto hulks was brought under control.

The changing makeup of automobiles that will be produced in the future will have significant impact on the operations of the scrap industry in the future. Vehicles will weigh less. The total amount of ferrous material will decrease, but the diversity of ferrous alloys will increase. The projected increase in plastics content imply that a future automobile will contain so much more material that can not be economically recycled with available technology (6-2, 6-3, 6-4). It is within this context that one has to examine the scrappage and reclamation potential of metal-plastic laminates.

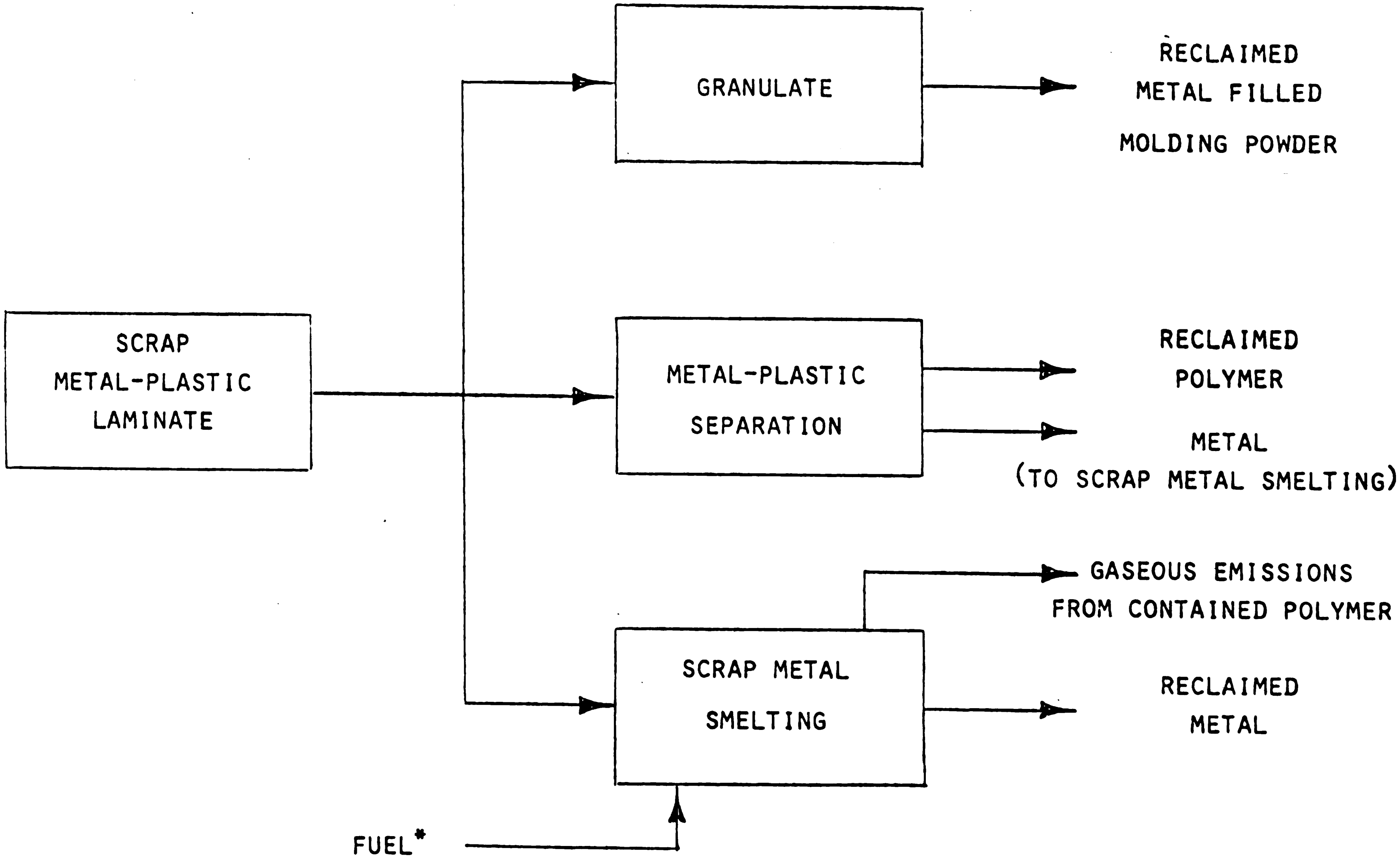
Metal-plastic laminate scrap will have a finite scrap value, but this value will be less than that now obtained for sheet metal scrap. This is because mixed materials, as a rule, have less scrap value than a homogeneous material. Conceptually, there are three options for materials reclamation from metal-plastic laminate offal, as outlined in Figure 6-3. These include granulation of the laminate to reclaim a metal filled molding powder. A second option is to separate the metal skins from the plastic core and then reuse each material separately. The third is to reclaim the laminate for its scrap metal content.

The first option, granulation of the laminate into a molding powder, was proposed by McKenna et al. (6-5) as a means of reclaiming aluminum-nylon laminate offal. McKenna examined the properties of plaques molded from ground laminate, and found that the physical properties of these samples compared favorably with the properties of samples obtained with various commercial formulations of nylon molding powders, as outlined in Table 6-1. The major concern is that a market has to be developed for such molding powders, and that this market has to be large enough to accommodate all the scrap molding powder the automotive industry could generate. The feasibility of this approach will also depend very much on the type of laminate being considered. It is doubtful that this approach would be applicable to steel faced laminates because of rusting of the steel. Properties of aluminum filled polyethylene or polypropylene may not warrant their reuse.

A second approach is to reclaim both the metal and the plastics contained in the offal. This entails a separation step of the various techniques that could be used, such as:

a) dissolution of the polymer in a suitable solvent, draining the polymer solution from the metal, and recovering the polymer from the solution;

b) heating the laminate under pressure to a temperature above the melting point of the polymer. The molten polymer exuded from the laminate is then separated from the metal; and



*POTENTIAL REDUCTION IN FUEL REQUIREMENTS

Figure 6-3

OPTIONS FOR MATERIALS RECLAMATION FROM METAL-PLASTIC LAMINATE OFFAL

PHYSICAL PROPERTIES OF PLAQUES MOLDED FROM GROUND LAMINATE SCRAP VERSUS REFERENCE MATERIALS*

PROPERTY	MODIFIED LAMINATE SCRAP	NYLON 6-6	MINERAL-REINFORCED NYLON 6-6	FIBERGLASS-REINFORCED NYLON 6-6
FLEXURAL MODULUS, MPA	5510	2140	6200	5860
FLEXURAL STRENGTH, MPA	125	109	152	200
HEAT DISTORTION TEMPERATURE, °C	200	80	143	252
IMPACT STRENGTH:				
IZOD, N-M/CM	4.8	3.2	3.2	6.4
GARDNER, N-M	1.0	18.1	7.5	1.7

*PROPERTIES FOR DRY, AS MOLDED SPECIMENS

SOURCE: L.W. MCKENNA ET AL, SAE 8000079

c) cryogenic shredding of the laminate at a temperature low enough to result in fracture of the metal-polymer bond, followed by either magnetic, density, or size separation of the polymer fragments. Of the three techniques, possibly only the last may be practical. While cryogenic shredding facilities exist, the process is not widely implemented. There is also a question as to whether the value of the materials recovered from this operation would warrant the entailed costs.

The third option is to reclaim laminates solely for their metal content. In the case of steel faced laminates with a 60 percent core volume ratio, the contained plastic represents only 10 percent of the total weight of the laminate. In case of an aluminum faced laminate with a core volume ratio of 75 percent, the aluminum content would range from about 40 to 50 percent by weight depending on the density of the core polymer. In both instances, the metal content should be high enough to justify reclamation of the laminate. As previously stated, the metal plastic laminate scrap will have less value than could be obtained for the face sheets if they were polymer free. In particular, the metal-plastic laminate scrap will have a lower bulk density. Metal units per unit volume will be lower than for polymer free sheet metal scrap. This will result in higher transportation costs for the laminate scrap because more volume is required to ship a given amount of metal. Furthermore, the lower metal content per unit volume will depress the value of the scrap to the smelters or furnace operators. The polymer core, however, because of its finite weight, will further add to the transportation costs. Decomposition of the polymer core in the metal smelting furnace will result in gas formation which could contain particulates and noxious fumes, and increase the duty requirements of environmental control systems. The extent to which this may occur will depend on the particular characteristics of the polymer present in the core, and its pyrolysis characteristics. Nylon, because of its nitrogen content, may be less desirable in a furnace than a polyolefin, for example. The use of fillers will add to slag formation. There is a possibility that the polymer might contribute to the energy requirements of the smelting operation. However, the inherent fuel value of the polymer contained in the core is unlikely to be used in most metal smelting operations now used for scrap reclamation.

Whether or not metal-plastic laminates would be recycled will ultimately depend on their acceptability by smelters and furnace operators. Because scrap steel has a lower value than scrap aluminum, any concerns which may constrain the reclamation of metal-plastic laminate scrap, will have greater impact on steel faced laminates than aluminum faced laminates.

The attitude of different steel companies with regards to the acceptability of steel faced laminate scrap as an acceptable feed stock for their furnace operations depends on whether or not the company is interested in developing laminates for the automotive market. Representatives of the four steel companies that have active laminate development programs are less concerned, and have fewer reservations about the reclamation of steel-plastic laminates, than did representatives of two steel companies that did not have any current interest in this technology (6-6, 6-7). The concerns of the latter, which included the low iron content per unit volume, the potential environmental hazards, and the low justifiable economic value of the scrap, were shared by a technical representative of the scrap industry (6-8), who considered metal-plastic laminates of interest as a good example of a product which was not designed to be easily recyclable.

It was generally agreed, however, that the presence of a small concentration of metal-plastic laminate in a scrap heat should have little effect on the operation of the furnace. It is to be noted that vinyl coated scrap is currently being reclaimed at low dilutions in a heat even though volatile chlorides are evolved when the vinyl is heated. Pyrolysis of the polymers being considered as cores for laminates would be less of an issue than the pryolysis of polyvinyl chloride.

Within the longer term context of recycling materials from junk cars, while laminates may be less desirable and profitable to reclaim than sheet metal, they would have inherently more value than fiber reinforced plastics that are an alternate materials substitution option.

CHAPTER 6 REFERENCES

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7.0 COST AND MANUFACTURE OF METAL-PLASTIC LAMINATES

This chapter summarizes the results of an analysis of the elements of costs of metal-plastic laminates. The principal cost elements considered were: a) the costs of contained materials in a laminate, and b) the costs and profit associated with converting the metal and plastic raw materials into a laminate sheet. The costs of the raw materials can be established with accuracy since most of the materials involved are standard items of commerce. Cost assumptions had to be made only for some specialty polymers. The costs of converting these raw materials into laminates are not well established. These will depend significantly on the assumed laminating process and the scale of operation. To arrive at such cost estimates, it was necessary to perform a preliminary manufacturing and cost analysis for various alternate lamination processes, including batch lamination on platen presses, continuous lamination with roll presses, and semi-continuous lamination on existing coil coating equipment.

The costs are presented on a per unit area basis rather than a per unit weight basis for ease of comparison. Since the lamination costs are essentially independent of thickness of the laminate, it follows from the above that the relative cost of laminate of given composition to a functionally equivalent homogeneous metal sheet will decrease with thickness, i.e. laminates become more competitive as the thickness of the steel sheet increases.

7.1 COST OF CONTAINED MATERIALS

The cost of the contained materials is equal to the sum of cost of the face sheets, the cost of the polymer core, and the cost of the adhesive if one is required.

7.1.1 Cost of Face Sheets

Materials of interest for face sheets include drawing quality cold rolled steel, either as is or coated with a variety of corrosion resistant materials, and a variety of aluminum alloys. Stainless steels were not considered in the analysis because of their high unit price. The costs per unit area of different sheet materials of interest as a function of sheet thickness is presented in Figure 7-1. The costs of sheet steel are the U. S. Steel Corp. base prices that went into effect on April 1, 1980. for the following grades of steel:

Sheet Thickness	Grade of Steel
0.4 mm of greater	cold rolled, drawing quality special killed
between 0.2mm and 0.4mm	single reduced black plate, Type D
0.2 mm or less	double reduced black plate

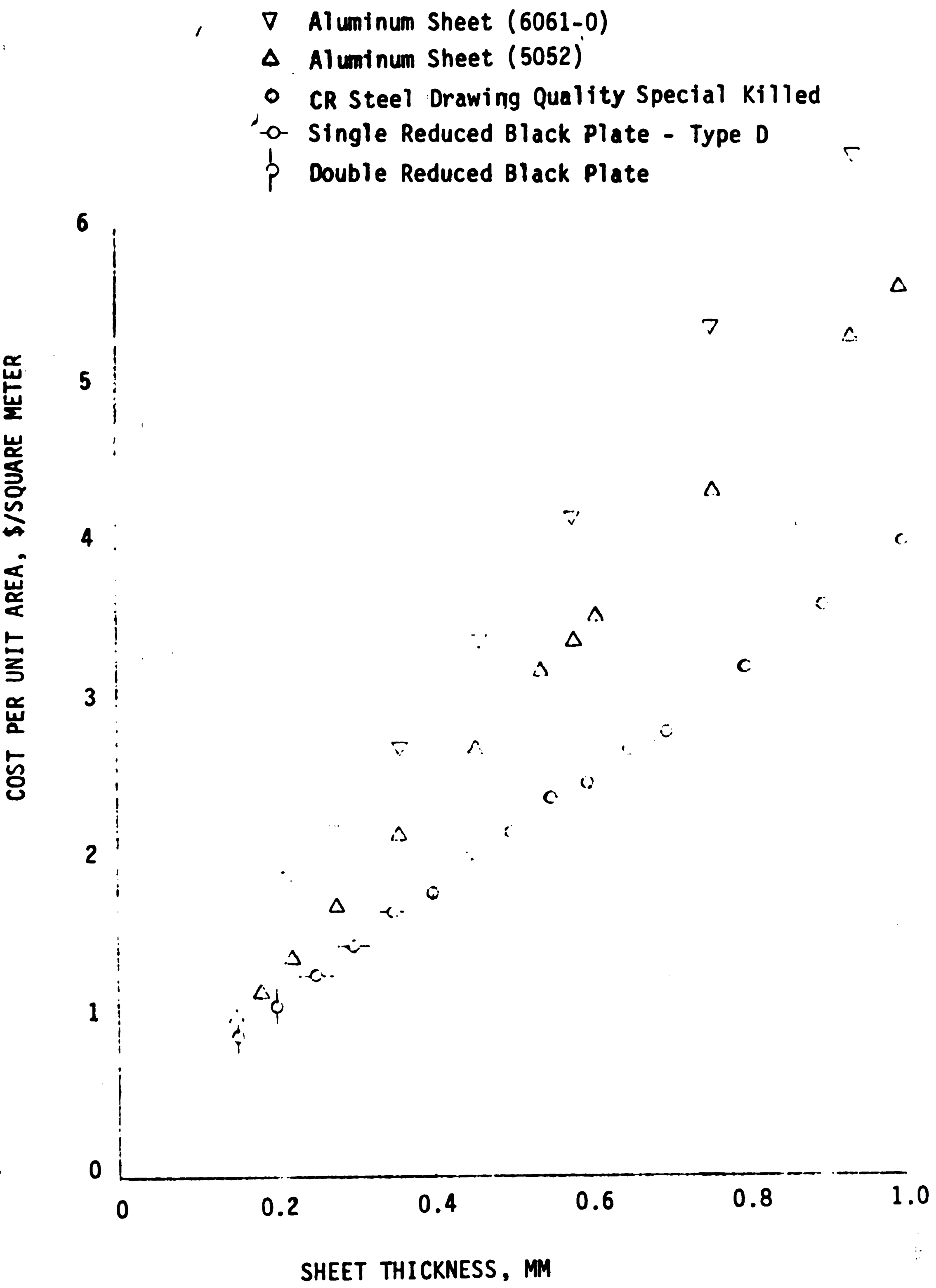


FIGURE 7-1 COST PER UNIT AREA OF SHEET METALS OF INTEREST AS A FUNCTION OF SHEET THICKNESS (1980 BASIS)

At the time, the base price for cold rolled sheet, Class I, was $21.90/cwt (7-1).

The surcharges that would apply, if various corrosion resistant coatings were applied to the steel sheet are summarized in Table 7-1. The surcharge for electrolytic chromium coating is that applied by U.S. Steel Corp. and the other steel manufacturers. The surcharges for galvanizing were estimated from the differences in the published prices of galvanized steel and cold rolled steel of different given thicknesses. The unit prices were unit weight that were given were first converted into equivalent unit prices per unit area. It was found that the price differential per unit area did not vary significantly with sheet thickness. The surcharge for aluminizing was estimated in a similar manner from the differences in the published prices of aluminized steel and cold rolled steel.

The cost of zincrometal coating will depend on whether the zincrometal is applied in a separate operation or in conjunction with the lamination of a steel-plastic sandwich. The estimates given in Table 7-1 are based on current tolling charges applied by one of the large coil coating operations (7-2).

The prices for the two aluminum alloys given in Figure 7-1 are the base prices for coiled sheet published by ALCOA on June 9, 1980, converted into price per unit area. At the time, the base price of 5052 alloy, 0.006 in. to 0.007 in. (0.15 mm to 0.18 mm) thick was $1.110/lb. ($2.442/kg). The price of aluminum alloy 6061-0 in its thinnest available commercial gauge of 0.0085 in. (0.22 mm) is $1.333/lb. ($2.933/kg) (7-3).

It is to be noted that the price per unit area of all the sheet metals considered decreases with decreasing thickness (even though the price per unit weight increases). The slopes of the price per unit area versus thickness curves are different for the aluminum alloys and for steel. As thickness decreases, the price per unit area of the aluminum alloys decreases more rapidly than that of steel. This most probably reflects the fact that aluminum is easier to roll than steel. At sheet thicknesses of 0.2 mm or less, there is very little difference (less than 10%) in the price per unit area of 5052 alloy and double reduced (unannealed) black plate. There is a greater difference in the unit price of 6061-0 alloy at its minimum thickness, and 5052 alloy, than between 5052 alloy and black plate of the same thickness.

7.1.2 Cost of Core Polymers

The prices of polymers of interest are given in Table 7-2. These are early 1980 list prices as reported in Modern Plastics (7-4, 7-5), except where noted. The price of talc filled polypropylene is a calculated value for a compounded material with a specific gravity of 1.32, the specific gravity of the core material in Bethlehem Steel Corp.'s developmental laminates (7-6).

TABLE 7-1

ADDITIONAL COST OF STEEL TREATED WITH CORROSION RESISTANT COATINGS

COATING TREATMENT	SURCHARGE $/M^2
ELECTROLYTIC CHROMIUM	0.04 - 0.08
GALVANIZING	0.35
ALUMINIZING (T-40)	0.70
ZINCROMETAL	0.50 - 1.00
ZINCROMETAL (ON LINE WITH LAMINATION)	0.20 - 0.40

TABLE 7-2

PRICE OF POLYMERS OF INTEREST

POLYMER	SPECIFIC GRAVITY	UNIT PRICE	
		$/LB	¢/CM^3
POLYETHYLENE	0.91	0.44	0.088
POLYPROPYLENE	0.91	0.44	0.088
POLYPROPYLENE, TALC FILLED	1.32	0.28[a]	0.081
POLYPROPYLENE, SELF-ADHERING COPOLYMER	0.91	0.70[b]	0.140
NYLON 6-6	1.14	1.34[c]	0.336
THERMOPLASTIC POLYESTER (PET)	1.34	0.90[d] 0.60	0.226 0.180

a) Calculated Value

b) Based on discussions with Hercules, Inc.

c) List price of nylon 6-6 molding powder

d) Current price of off-specification extrusion grade nylon 6-6 on the secondary market

This filled polymer contains 54.3 percent by weight polypropylene, with the balance being talc. The price of the compounded material is based on this material ratio, the price for polypropylene given in Table 7-2, a price of 0.045/lb (0.10/kg) for talc (7-7), and a compounding cost of \$0.02/lb (\$0.044/kg) based on a recent cost analysis of compounding operations by Smoluk (7-8). The price of the self-adhering polypropylene co-polymer was based on discussions with representatives of Hercules Inc. who would be the supplier of this material (7-9). Two prices are reported for nylon 6-6. The higher price is the current list price for nylon 6-6 molding powder. The second is the current price for off-specification extrusion grade nylon 6-6 on the secondary market, according to a broker who handles this material (7-10). This range of prices is given because, in projecting the future cost of aluminum-nylon laminates, Monsanto Corporation claims that the price of the contained nylon 6-6 would be less than the current price of nylon 6-6 molding pwoder, so as to allow the laminate to be priced at a level intermediate to those that would be prevailing for aluminum sheet and steel sheet at the time the aluminum-nylon laminates would become commercially available (7-11). Not being privy to Monsanto's internal pricing for the specific grade of nylon 6-6 that would be used in its laminates, for lack of better data, the current scrap value of nylon 6-6 extrusion grade polymer was taken as an estimate of the lower end of range of the possible price of nylon 6-6 that would be applicable to the manufacture of metal-plastic laminates.

Thus, the core acts as filler between the face sheets. The various polymers should be compared on a price per unit volume basis. The least cost polymer is talc filled polypropylene, which is about 10 percent less expensive than the unfilled polyolefin homopolymers. The self adhering polyolefin is the next most expensive material, followed by PET which is about twice as expensive as polyethylene or polypropylene. Even at its scrap value, nylon 6-6 is the most expensive polymer on the list.

7.1.3 Cost of Adhesives

As previously mentioned in Chapter 2, very little information is available on the specific adhesives which would be used in conjunction with metal-plastic laminates that do not have self-adhering cores. Cost data was obtained for Morprime™, a specific adhesive being evaluated for a variety of polypropylene cored laminates. Morprime™ is a proprietary dispersion of a polypropylene organosol in an alphatic hydrocarbon liquid. The commercial product contains 15 percent by weight of active ingredient. It is applied at a rate of 1.5 to 2.0 gr/m^2 of metal surface. The current of Morprime dispersion is \$4.20/lb (\$9.24 (kg)), which is equivalent to 6.2¢ per gram of active ingredient (7-12). Based on an application rate of 1.5 gr/m^2 per face sheet, this is equivalent to a cost of \$0.185/square meter of laminate.

7.1.4 Effect of Laminate Composition on Laminate Cost

Because the thickness of the facings and the core can be varied independently, many different laminates can be functionally equivalent to a given metal sheet of specified thickness. Chapter 3 presented an analysis of the effect of laminate dimensions and composition on the relative thickness and relative weight of a laminate to a sheet of steel of given stiffness, assuming different functional equivalency criteria. The same approach will be used in this section to establish the effects of laminate dimensions and composition on the relative cost of raw materials in the laminate to the cost of a functionally equivalent steel sheet.

Figure 3-1 presented the variation of the ratio of the thickness of a laminate to that of sheet steel of equivalent stiffness as a function of the core volume ratio, for laminates with steel skins and aluminum skins. Stiffness was assumed to vary either as the square or the cube of thickness of the laminate. Once the thickness of the steel sheet used as a basis of reference is established, the curves in Figure 3-1 fully define the total thickness of the laminate, and the thickness of the polymer core. This also defines the thickness of the faceskins if the thickness of the adhesive is neglected. Figure 3-3 is a plot comparable to Figure 3-1 which more explicitly presents the data in terms of the relative thickness of the face skins to the thickness of the reference steel sheet.

Within the total cost of a laminate on a unit area basis, only the cost of the face sheets and of polymer vary as the dimensions of the laminate change. The cost of the adhesive (if needed) and the lamination costs are constant. The change in the cost of a laminate incurred by changing the relative amount of contained materials will reflect changes in the total of costs of the face sheets and of the polymer core.

Cost calculations were performed for steel and aluminum faced laminates, with either a polyolefin or a nylon 6-6 core, that were equivalent in stiffness to 0.8 mm thick steel sheeting. The calculations were also performed for steel faced laminates comparable in stiffness to a 1.6 mm thick steel sheet. The price of the metal sheets of different thicknesses were those reported for steel and aluminum alloy 5052 in Figure 7-1. The price of the reference steel sheet is \$3.20 per square meter for 0.8 mm steel, and \$6.41 per square meter for 1.6 mm steel. The price of the polymers are 0.088¢/cm^3 for the polyolefins and 0.336¢/cm^3 for nylon 6-6 (Table 7-2). The polymers and their prices were chosen to establish the effects of a wide range of polymer prices. The cost of polymer per unit area is the product of these unit volume prices times the thickness of the core (in cm.). The calculations were performed for values of the core volume ratio that ranged from 0.10 to 0.80. It was presumed that laminates with a core volume ratio outside this range would have technical drawbacks which would limit or preclude their use, as discussed in Chapter 3.

The results of the calculations are presented in Figures 7-2 and 7-3. The curves presented in Figure 7-2 assume that stiffness of a laminate is proportional to its thickness to the third power, whereas those presented in Figure 7-3 are based on a variation of stiffness with the square of the laminate thickness.

The various curves in Figure 7-2 and 7-3 definitely indicate that the relative cost of contained materials in a laminate to the cost of a functionally equivalent steel sheet depends on the choice of materials used, their relative amounts, the equivalence factor used, and the thickness of the reference steel sheet.

In general, steel faced laminates are less costly than aluminum laminates. This cost differential derives principally because the aluminum faced laminates have to be thicker than the steel faced laminates to maintain a given stiffness, and thus contain more polymer. As previously indicated in Figure 7-1, the cost differential between aluminum and steel, or a unit area basis, in the thickness range of interest, is relatively small.

Secondly, polyolefin cored laminates are less costly than nylon core laminates. The cost of aluminum faced laminates is much more sensitive to the cost of the polymer than is the cost of the steel faced laminates. This also follows from the fact that aluminum faced laminates have to be thicker than steel faced laminates to maintain constant stiffness.

Third, the relative costs of a laminate to steel depends on the thickness of the reference steel sheet. Under otherwise similar conditions, the raw materials costs for laminates comparable to a 1.6 mm steel sheet are lower than those for laminates comparable to an 0.8 mm sheet. This follows because the face sheets of the laminates comparable to the thicker steel are twice as thick as face sheets of the laminates comparable to the thinner steel, and are therefore proportionately less costly. The base price, on a per unit weight basis is constant for cold rolled steel sheet over the range of thicknesses from 0.063 in. (1.60 mm) to 0.028 in. (0.71 mm), but increases with decreasing thickness for thinner gauges.

Fourth, the relative costs of a laminate to steel depend on the equivalency factor assumed. The cost of contained materials is higher if it is assumed that $S \sim t^2$ than if $S \sim t^3$. The proportional effect is much greater with aluminum faced laminates than with steel faced laminates. This also follows from differences in relative thickness.

For a given set of parameters, there is a value of α for which the ratio of the cost of contained materials in a laminate to the cost of equivalent steel has a minimum value. These data are presented in Table 7-3.

In comparison to 0.8 mm thick steel, the minimum cost of materials for steel faced laminates will be approximately 72

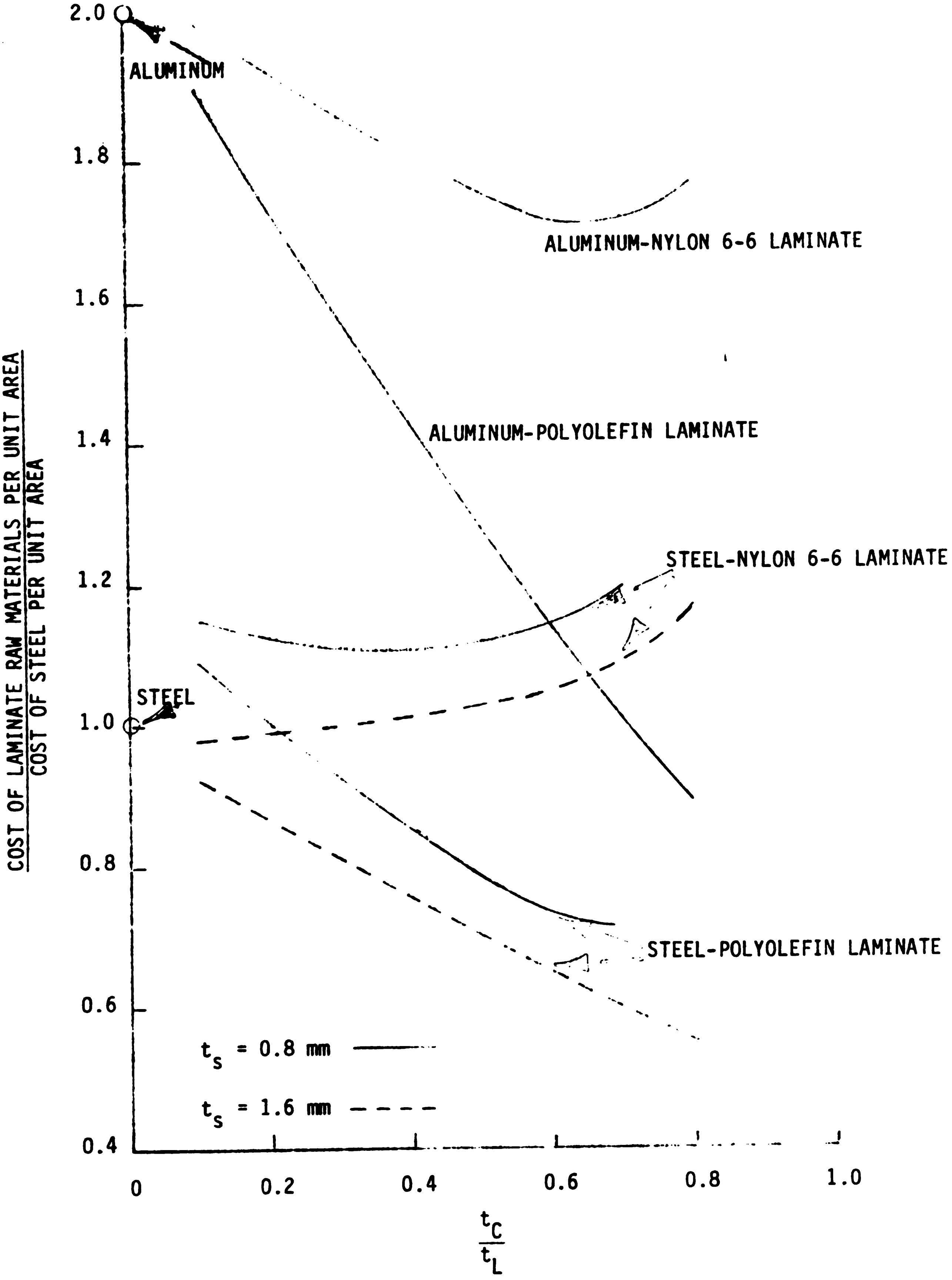


FIGURE 7-2. RELATIVE COSTS OF LAMINATE RAW MATERIALS AND STEEL PER UNIT AREA AS A FUNCTION OF CORE VOLUME RATIO AND THICKNESS OF STEEL SHEET USING FLEXURAL STIFFNESS AS THE EQUIVALENCE CRITERION ($S \sim t^3$)

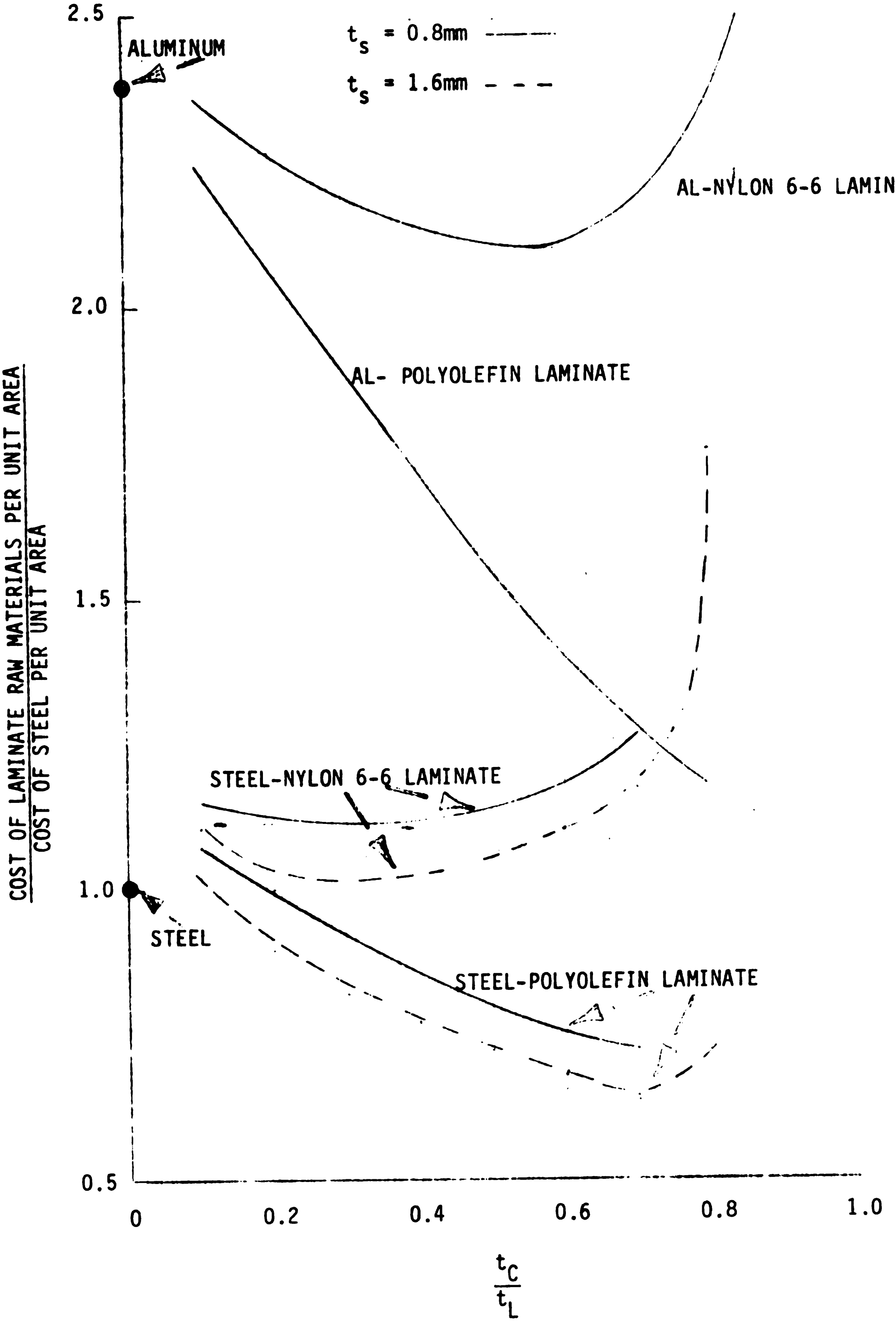


FIGURE 7-3. RELATIVE COSTS OF LAMINATE RAW MATERIALS AND STEEL PER UNIT AREA AS A FUNCTION OF CORE VOLUME RATIO AND THICKNESS OF STEEL SHEET USING LOCAL BUCKLING OR OIL CANNING AS THE EQUIVALENCE CRITERION ($S \sim t^3$)

TABLE 7-3 MINIMUM VALUE OF THE RATIO OF THE COST OF RAW MATERIALS IN A LAMINATE TO THE COST OF A STEEL SHEET OF EQUIVALENT STIFFNESS

THICKNESS OF THE REFERENCE STEEL SHEET, MM	STIFFNESS CRITERION		FACING MATERIAL	CORE MATERIAL	MINIMUM MATERIALS COST RATIO	CORRESPONDING CORE VOLUME RATIO
	$S \sim t^2$	$S \sim t^3$				
0.8		x	Steel	Polyolefin	0.72	0.70
"	x		Steel	Polyolefin	0.73	0.70
"		x	Steel	Nylon 6-6	1.11	0.40
"	x		Steel	Nylon 6-6	1.10	0.30
"		x	Aluminum	Polyolefin	0.89	0.80
"	x		Aluminum	Polyolefin	1.16	0.80
"		x	Aluminum	Nylon 6-6	1.71	0.65
"	x		Aluminum	Nylon 6-6	2.22	0.57
1.6		x	Steel	Polyolefin	0.56	0.80
"	x		Steel	Polyolefin	0.65	0.70
"		x	Steel	Nylon 6-6	0.98	0.10
"	x		Steel	Nylon 6-6	1.02	0.30

percent of the cost of steel for polyolefin cored laminates, and 10 percent higher than the cost of steel for a nylon cored laminate. The minimum core volume ratios corresponding for each core are 0.70 for the polyolefin, and 0.40 for the nylon if $S \sim t^3$, and 0.30 if $S \sim t^2$. The costs of contained materials in steel-nylon cored laminates are insensitive to the core volume ratio, and vary by less than ten percent over the range examined. The materials cost ratio for steel-polyolefin laminates are much more sensitive to the core volume ratio and show a definite minimum at a core volume ratio of 0.70.

The same general characteristics are noted in terms of the relative costs of steel faced laminates and 1.6 mm sheet steel. The minimum cost ratios, however, are lower in this instance than with 0.8 mm reference steel sheet. The minimum materials cost ratio for a polyolefin core is 0.56 at a core volume ratio of 0.80, if $S \sim t^3$, and 0.65 at a core volume ratio of 0.70, if $S \sim t^2$. With a nylon core, the minimum ratio is approximately 1, with little variation between values of the core volume ratio of 0.1 and 0.6.

For aluminum faced laminates designed to replace 0.8 mm steel, with polyolefin cores, the relative materials costs decrease with increasing values of the core volume ratio throughout the range investigated. The minimum value reported is the value at a core volume ratio of 0.8, but is not the absolute minimum which lies above this value. Depending on whether the equivalency is assumed to vary as t^3 or t^2, the relative material costs are either 11 percent lower or 16 percent higher than the cost of steel. With a nylon core, the minimum ratio of material costs is 71 percent higher, or 122 percent higher, depending on whether $S \sim t^3$ or $S \sim t^2$, The corresponding values of the core volume ratios are 0.65 and 0.57.

The minimum material cost ratios of all these laminates are lower than the ratio of the cost of aluminum alloy 5052 to that of 0.8 mm steel. With $S \sim t^3$, this ratio has a value of 2.0, and with $S \sim t^2$, this value is 2.4.

In summary, the cost of contained metal and plastic in a laminate, on a functionally equivalent basis, can be: a) significantly less than that of steel for polyolefin-steel laminates; b) comparable to that of steel for steel-nylon and aluminum-polyolefin laminates; c) higher than that of steel but less than the cost of aluminum alloy for aluminum nylon 6-6 laminate, based on the highest possible cost of nylon 6-6.

These results are comparable with the results previously presented by Miller who used a different format (7-13). These costs, however, do not present, by any means, the total cost of a laminate to a user since they do not include the cost of converting the metal sheets and polymer core into a laminate. These costs will be discussed in the next section.

7.2 METAL-PLASTIC LAMINATE MANUFACTURING COST ANALYSIS

The conversion of thin metal sheets and a sheet of polymer into metal-plastic laminate entails the following principal steps:

a) Cleaning and pre-treatment of the metal sheets, as required.

b) Application of adhesive to the metal sheets, as required.

c) Assembly of a metal sheet- polymer sheet-metal sheet sandwich.

d) Heating the metal-plastic-metal sandwich under pressure to a temperature above the melting point of the core polymer or adhesive, to form a metal-plastic bond.

e) Cooling the sandwich to a temperature below the melting or softening point of the core polymer or adhesive, thus forming the laminate.

If the operation was large enough, polymer flake could be extruded into sheet in-house in a parallel operation.

The laminating process can either be carried out in a batch mode to produce flat sheets of laminate or in a continuous or semi-continuous mode to produce continuous coils of laminates. Production capacity and costs vary widely with the choice of operation. Projected costs as a function of the mode of operation are given in Table 7-4. These costs are based on the manufacturing analysis presented as Appendix D.

The range in output levels and sandwich lamination costs represent 2000 hr/year to 6000 hr/yr operations. Polymer sheet extrusion costs are those entailed in converting plastic pellet into sheet. The costs associated with material losses, handling and shipping are assumed to be 16 percent of the cost of the contained materials--10 percent for handling and shipping, 6 percent for materials losses and scrappage.

As can be seen in Table 7-4, laminating costs associated with batch lamination, even with sequential presses, which may not be a technically feasible approach, are significantly higher than those engendered by continuous lamination. Most of the metal-plastic laminates being developed for automotive use are currently made in a batch mode on platen presses because of ease and expediency. The resulting costs and production rates preclude the use of laminates made in this manner from ever being used on production vehicles. In terms of any significant production use by the automobile industry, laminates will have to be made on a continuous basis because of improved economics, as is evident from Table 7-4, improved consistency and quality of the product, and improved product form. With a continuous lamination

TABLE 7-4

ESTIMATED COST OF LAMINATE FABRICATION AS A FUNCTION OF PROCESS AND PRODUCTION LEVEL (EXCLUSIVE OF COST OF CONTAINED MATERIALS)

PROCESS	BATCH OPERATION MULTI-PLATEN PRESS	BATCH OPERATION SEQUENTIAL PRESSES	CONTINUOUS ROLL PRESS	CONTINUOUS HIGH VOLUME	SEMI-CONTINUOUS (TOLL BASIS)
Estimated Capital Investment in Physical Plant, $\$10^6$	0.85	1.35	1.6	18	existing facilities
Laminate Output, 10^3 m^2/yr	60 - 180	350 - 1050	1000 - 3000	17,000	8,000
		COST CONTRIBUTION, $\$/m^2$ of Laminate			
Sandwich Lamination	14.50 -6.61	3.60 - 1.70	2.12 - 0.88	0.85	1.80
Polymer Sheet Extrusion	0.20	0.20	0.20	included in above	0.20
Material Losses, Handling, Shipping, etc.*	0.50	0.50	0.50	0.50	0.50
TOTAL	15.20 - 7.30	4.30 - 2.40	2.82 - 1.58	1.35	2.50

* Nominal value used for calculations. Estimate varies from about $\$0.40/m^2$ to $\$1.00/m^2$ depending on specific composition of laminate.

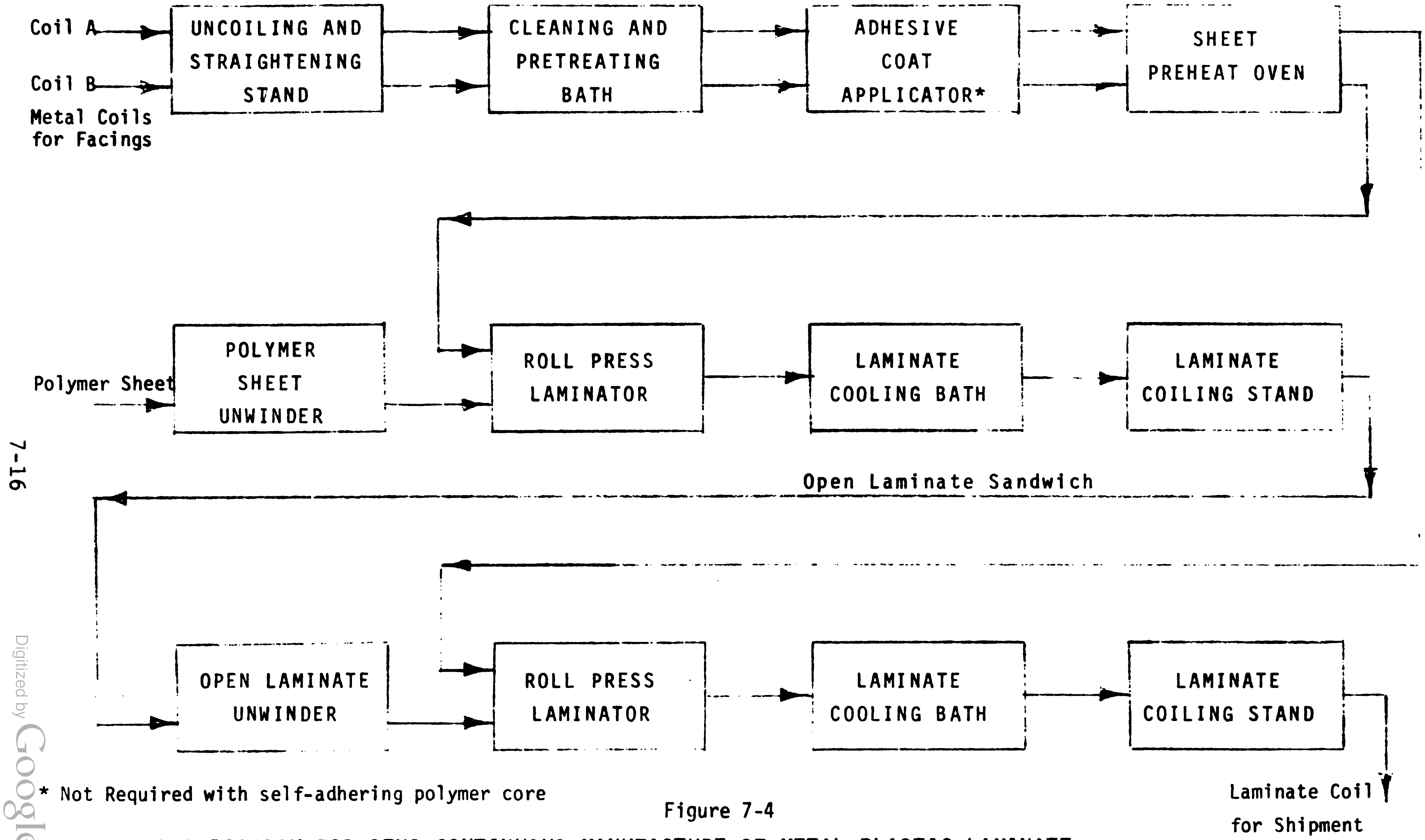
plant, the metal-plastic laminate would be available in coils, which the automotive industry is used to handling rather than being available in sheets of limited dimensions.

Continuous lamination is an established technology. Consolidated Aluminum Corp. has a continuous laminating facility in Benton, Kentucky that can produce Alucobond[R] aluminum polyethylene laminate in widths of up to 4 ft. (122 cm), as does Alusuisse, Consolidated Aluminum Corp.'s parent company, in Europe (7-14). Mitsui Petrochemical Industries Ltd. has a comparable facility in Japan (7-15). Dow Chemical USA indicated that they have developmental lamination facilities in their laboratories that could provide initial quantities of laminate (7-16). Plastro-tech Industries, Inc. recently announced the projected startup of a continuous laminating plant which may be capable of producing metal-plastic laminates that would be of interest to the automotive industry. (7-17).

It was estimated that a dedicated manufacturing facility for the continuous manufacture of a metal plastic laminate would require an investment of about $2 million for a facility with a production capacity of 1 million square meters/year, and about $18 million for a facility with a production capacity of 17 million square meters/year. These production levels are based on 6,000 hours per year of operation.

Before suppliers invest in such facilities, however, demonstrated markets for the metal-plastic laminates that will be produced will have to exist. The classic supply-demand dichotomy that often plagues the introduction of any new material (capital investments in manufacturing, that would allow a material to be competitive, are not made because the material is currently not competitive, and the material is presently too expensive because it is not made in the less costly manner which would require the investment of capital which . . . .) may be circumvented in the case of metal-plastic laminates because these materials could be manufactured by a two-step process on existing coil coating equipment for about $2.50/m^2 (\$0.23/ft^2) above the cost of contained materials on a toll basis. As will be subsequently discussed, at this cost, laminates could be considered as viable materials by the automotive industry.

The coil coating industry's function is to apply a variety of organic finishes and coatings to sheet metal to provide decorative or corrosion resistant finishes. These same facilities can also be used to apply polymer film to a metal sheet. By performing this operation sequentially with two sheets of metal, it is possible to form a metal-plastic-metal sandwich, as has been demonstrated by Pre-Finish Metals Inc. of Elkgrove Village, IL. This company has already prepared a 4000 lb. (1800 kg) coil of adhesively bonded steel-polypropylene-steel laminate in this manner, as outlined in Figure 7-4, and is currently modifying its equipment to accommodate coils weighing up to 20,000 lbs. (9000 kg) (7-19). The costs of semi-batch lamination given in Table 7-4



* Not Required with self-adhering polymer core

Figure 7-4

PROCESS DIAGRAM FOR SEMI-CONTINUOUS MANUFACTURE OF METAL-PLASTIC LAMINATE are based on the operations of a dedicated high volume laminating facility, but with a lower output to reflect the need for two passes in the machine and coil change-over time.

7.3 PROJECTED USER COST OF METAL-PLASTIC LAMINATES

The projected costs of metal-plastic laminates to the user will be the sum of the cost of contained materials, as discussed in section 7-1, and the conversion costs given in section 7-2.

The projected costs of various metal-plastic laminates that would be likely to be used by the automobile industry are presented in Tables 7-5 and 7-6. Table 7-5 presents the weight and costs, on a unit area basis, of various laminates, and of 5052 aluminum alloy sheet that could be used instead of 0.80 mm thick steel sheet. Laminate stiffness is assumed to vary as the laminate thickness squared. This is a more conservative assumption than the thickness cubed relation which could have been used. The steel faced laminates are somewhat overdesigned for this application, (neglecting denting considerations), but were deemed to be the thinnest and lightest material that would be available, given current annealing practices in the steel industry, as previously discussed in other chapters. Table 7-6 presents comparable data for laminates that would be used to replace 1.6 mm thick steel.

For the nearer term, total costs are projected on the basis of semi-continuous lamination in a coil coating facility, at a conversion cost of $\$2.50/m^2$ for the thinner laminates, and $\$3.00/m^2$ for the thicker laminates. These differences arise from differences in the amount of material that has to be processed and scrapped. Differences in scrappage and handling costs for the various material combinations were neglected for these calculations, as was the cost of adhesive, if required, since these cost variations are within the accuracy of the estimates. For the longer term, the costs developed for a continuous high volume manufacturing facility were used. The lamination charges were now assumed to be $\$1.35/m^2$ for the thinner materials, and $\$1.85/m^2$ for the thicker materials.

A range of costs is given for the nylon 6-6 cored laminates to reflect the uncertainty of the price of the nylon 6-6 that would be applied to the laminates in production.

In the nearer term, all the laminates considered as replacement for 0.8 mm steel sheet, are intermediate in price to steel and aluminum, except for the aluminum-nylon laminate. The least expensive steel-filled polypropylene-steel laminate would be 60 percent more expensive than 0.8 mm steel sheet. In the longer term, all the laminates, including aluminum-nylon 6-6 laminate based on the lower cost estimate of nylon 6-6, would be less expensive than 5052 aluminum alloy. They would still be more

TABLE 7-5

WEIGHT AND COST PER UNIT AREA OF SHEET MATERIALS OF INTEREST OF COMPARABLE[a] PERFORMANCE TO STANDARD AUTO SHEET STEEL (0.80 MM THICK)

MATERIAL	THICKNESS mm	CORE VOLUME RATIO α	WEIGHT/AREA kg/m^2	COST OF CONTAINED MATERIALS \$/m^2	PROJECTED COST OF PRODUCT	
					NEARER TERM[b] \$/m^2	LONGER TERM[c] \$/m^2
Steel - Polyolefin	1.0	0.6	3.682	2.66	5.16	4.01
Steel - Polypropylene Copolymer	1.0	0.6	3.682	2.99	5.49	4.34
Steel - Filled Polypropylene	1.0	0.6	3.936	2.62	5.12	3.97
Steel - Nylon 6-6	1.0	0.6	3.828	3.18-3.77	5.68-6.27	4.53-5.12
Aluminum - Polyolefin	1.9	0.8	2.407	3.77	6.27	5.12
Aluminum - Nylon 6-6	1.5	0.6	2.694	5.72-6.72	8.22-9.22	7.07-8.07
Aluminum (5052)	1.35	-	3.649	7.60	7.60	
Cold Rolled AK Steel	0.80	-	6.280	3.20	3.20	
Cold Rolled AK Steel	0.89	-	6.987	3.56	3.56	

Notes

a) Aluminum and aluminum faced laminates are functionally equivalent (Et^2 = constant) to 0.80 mm thick sheet steel. Steel faced laminates are minimum gauge products contemplated by suppliers. These laminates are functionally equivalent to 0.89 mm steel sheet on the basis chosen.

b) Based on semi-continuous manufacture on a toll basis in an existing coil coating facility @ \$2.50/m^2

c) Based on a large scale (17 million square meter/year) dedicated facility @ \$1.35/m^2

TABLE 7-6

WEIGHT AND COST PER UNIT AREA OF SHEET MATERIALS OF INTEREST
OF COMPARABLE [a] PERFORMANCE TO HEAVY GAUGE SHEET STEEL (1.6 MM THICK)

MATERIAL	THICKNESS mm	CORE VOLUME RATIO α	WEIGHT/AREA kg/m^2	COST OF CONTAINED MATERIALS \$/m^2	PROJECTED COST OF PRODUCT NEARER TERM[b] \$/m^2	PROJECTED COST OF PRODUCT LONGER TERM[c] \$/m^2
STEEL - POLYOLEFIN	1.8	0.6	6.622	4.35	7.35	6.20
STEEL - POLYPROPYLENE COPOLYMER	1.8	0.6	6.622	4.91	7.91	6.76
STEEL - FILLED POLYPROPYLENE	1.8	0.6	7.079	4.28	7.28	6.13
STEEL - NYLON 6-6	1.8	0.6	6.884	5.96-7.03	8.96-10.03	7.81-8.88
ALUMINUM (5052)	2.7	-	7.298	14.95	14.95	
COLD ROLLED AK STEEL	1.6	0.6	12.560	6.41	6.41	

Notes

a) Substitution materials are functionally equivalent (Et^2= Constant) to 1.6 mm thick steel

b) Based on semi-continuous manufacture on a toll basis in an existing coil coating facility @ \$3.00/m^2

c) Based on a large scale (17 million square meter/year) dedicated facility @ \$1.85/m^2

expensive than 0.8 mm steel. In this case, the cost differential between steel-filled polypropylene-steel laminate and 0.8 mm steel would be approximately 24 percent. These additional costs would be offset by the weight savings that would be derived from using the laminates. Table 7-7 outlines the cost and weight changes that would ensue from using various laminates, or aluminum alloy 5052, instead 0.8 mm steel in a component. The calculated cost penalty per unit weight saved presented in Table 7-7 has to be used with caution since it is based on finished component weight. The actual cost penalty will be different because of scrappage and credits for secondary weight savings. The scrappage rate will have a marked influence on the manufacturing cost penalty as will be discussed in more detail in the next chapter. However, the values given in the last column allow one to rank the various laminates among themselves and with aluminum. Even for the nearer term, the laminates compare favorably with aluminum.

Laminates designed to replace thicker, 1.6 mm steel sheet are proportionately less expensive than laminates designed to replace 0.8 mm steel. In the nearer term, steel polyolefin laminates could be only 14 percent more expensive than 1.6 mm steel sheet, and in the longer term, these laminates could be less expensive than 1.6 mm steel. The cost penalties per unit weight for these thicker laminates, as indicated in Table 7-8, become negligible, or even negative, for the polyolefin laminates. These lower costs for the thicker laminates follow because the conversion costs become a smaller fraction of the total costs.

WEIGHT SAVINGS AND COST PENALTIES INCURRED WITH SUBSTITUTION OF STANDARD AUTOMOBILE SHEET STEEL (0.80 mm THICK) BY SHEET MATERIALS OF INTEREST

MATERIAL	WEIGHT SAVED PER UNIT AREA		ADDITIONAL COST OF MATERIALS PER UNIT AREA		COST PENALTY PER UNIT WEIGHT SAVED*	
			NEARER TERM	LONGER TERM	NEARER TERM	LONGER TERM
	kg/m^2	Percent	$\$/m^2$	$\$/m^2$	\$/kg	\$/kg
STEEL POLYOLEFIN (t = 1.0 mm, α = 0.6)	2.598	41.4	1.96	0.81	0.75	0.31
STEEL-POLYPROPYLENE COPOLYMER (t = 1.0 mm, α = 0.6)	2.598	41.4	2.29	1.14	0.88	0.44
STEEL-FILLED POLYPROPYLENE (t = 1.0 mm, α = 0.6)	2.344	37.3	1.92	0.77	0.82	0.33
STEEL-NYLON 6-6 (t = 1.0 mm, α = 0.6)	2.452	39.0	2.48-3.07	1.33-1.92	1.01-1.25	0.54-0.78
ALUMINUM-POLYOLEFIN (t = 1.9 mm, α = 0.8)	3.873	61.7	3.07	1.92	0.79	0.50
ALUMINUM-NYLON 6-6 (t = 1.5 mm, α = 0.6)	3.586	57.1	5.02-6.02	3.87-4.87	1.40-1.68	1.08-1.36
ALUMINUM (5052) (t = 1.35 mm)	2.631	41.9	4.40		1.67	

* Values presented do not include effect of scrappage losses or of any resulting secondary weight savings

TABLE 7-8

WEIGHT SAVINGS AND COST PENALTIES (SAVINGS) INCURRED WITH SUBSTITUTION OF HEAVY GAUGE SHEET STEEL (1.6 MM THICK) BY SHEET MATERIALS OF INTEREST

MATERIAL	WEIGHT SAVED PER UNIT AREA		ADDITIONAL COST* OF MATERIALS PER UNIT AREA		COST PENALTY* PER UNIT WEIGHT SAVED**	
			NEARER TERM	LONGER TERM	NEARER TERM	LONGER TERM
	kg/m^2	Percent	$\$/m^2$	$\$/m^2$	$/kg	$/kg
STEEL-POLYOLEFIN (t = 1.8 mm, α = 0.6)	5.938	47.3	0.94	(0.21)	0.16	(0.04)
STEEL-POLYPROPYLENE COPOLYMER (t = 1.8 mm, α = 0.6)	5.938	47.3	1.50	0.35	0.25	0.06
STEEL-FILLED POLYPROPYLENE (t = 1.8 mm, α = 0.6)	5.481	43.7	0.87	(0.28)	0.16	(0.05)
STEEL-NYLON 6-6 (t = 1.8 mm, α = 0.6)	5.676	45.3	2.55-3.62	1.40-2.47	0.45-0.64	0.25-0.44
ALUMINUM (5052) (t = 2.7 mm)	5.262	41.9	7.15		1.36	

* Values in parentheses are cost savings

** Values presented do not include effect of scrappage losses or of any resulting secondary weight savings.

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8.0 AUTOMOTIVE APPLICATIONS OF METAL PLASTIC LAMINATES CASE STUDY ANALYSIS

8.1 INTRODUCTION

Experience to date with metal-plastic laminates as materials of construction for automotive components has been limited to specialty vehicles and the fabrication of prototype components for test and evaluation. The use of 4mm thick Alucobond^R aluminum-polyethylene laminate in the Marathon electric vehicle was discussed in Section 6.1. This laminate was also used to fabricate the floor pan and firewall of the prototype Briggs & Stratton hybrid vehicle which was unveiled earlier this year (8-1). The recent technical and business press has been replete with articles in which a wide variety of proposed potential automotive applications of metal-plastic laminates are mentioned (8-2 to 8-10). Some of these suggestions are listed in Table 8-1. Only some of these proposed applications of metal-plastic laminates appear reasonable based on material properties and the design, fabrication, repair and scrappage constraints outlined in the previous chapters. Furthermore, only vague references are made, at best, to the cost and manufacturability of these proposed metal-plastic laminate components.

In order to arrive at a better assessment of the likely automotive applications of metal-plastic laminates, Pioneer Engineering and Manufacturing Company was retained to examine the various individual components of an automobile that are now fabricated out of sheet metal, and identify those components which would be reasonable applications of metal-plastic laminates. The two test case vehicles chosen were a standard 1978 4-door hatchback Chrysler Omni passenger automobile, and a 1980 Ford F-150 pick-up truck. These two vehicles were specifically chosen because Pioneer had previously completed a detailed tear down and parts identification analysis on each of these vehicles under prior NHTSA funded programs. The final report of each of these studies (8-11, 8-12) lists all the major components, and their sub-elements, identifying the weight of the part, the material of construction, and for many sheet metal component, the gage of stock used. These data were used to develop estimates of current sheet metal usage for both of these vehicles, both in terms of weight and surface area.

The surface area of sheet metal in a finished component was calculated from the weight and gage reported in the Pioneer reports by the following equation:

$$A_1 = \frac{W_p}{(t)\ (144)\ (\rho)} \qquad (8\text{-}1)$$

where:

A_1 = calculated part area, ft^2

TABLE 8-1

AUTOMOTIVE APPLICATIONS OF METAL-PLASTIC LAMINATES MENTIONED IN THE RECENT TECHNICAL PRESS

- SEAT BACKS
- SEAT FRAMES
- AIR CLEANER COVERS
- MISC. COVERS
- SPARE TIRE COVERS
- NARROW BODY PANELS
    - PICK-UP TRUCK FRONT BODY PANEL
    - VAN COWL
    - REAR DECK LIDS
- LOAD FLOORS
- INTERIOR TRIM
- FANS
- OIL PANS
- TRUCK TRAILER SIDES

W_p = reported part weight, lbs.

t = reported thickness, in

ρ = density of sheet metal used, lbs/in^3

The current aggregate use of sheet metal in the Chrysler Omni auto and the Ford F-150 truck is presented in Tables 8-2 and 8-3 respectively. Approximately 332 ft^2 (30.8 m^2) of sheet metal weighing 475 lbs (216 kg) are used on the Omni. Approximately 530 ft^2 (49.2 in^2) of sheet metal weighing 838 lbs (381 kg) are used on the Ford F-150. For both vehicles, the weight of the sheet metal components corresponds to 23 percent of the vehicle curb weight. The distribution of sheet metal on each of these vehicles is given in Table 8-4. Appearance parts and other body panels account for about 80 percent of total sheet metal use for both vehicles. For the Omni, use of sheet metals accounts in appearance parts is about the same as for other body panels. For the F-150 truck, appearance parts, because of the large exposed deck, represent nearly half of the sheet metal use and other body panels account for only 30 percent of the total. The other applications of sheet metal amount to about 20 percent of the total. These parts tend to be of heavier gage than the panels that constitute the majority use, since it is noted that the weight percentage of sheet metal used in miscellaneous parts is slightly higher than its area percentage.

Tables 8-2 and 8-3 are the "wish list" of the developers of metal-plastic laminates in that they summarize the potential utilization of laminates in a typical automobile and light duty truck.

Pioneer was provided with the technical and cost information on metal-plastic laminates presented in Table 8-5, and the guidelines presented in Table 8-6. With this information, and based on the automotive experience of its staff, Pioneer reviewed the "wish list", and selected a number of specific components where the technical risk of using metal-plastic laminates would be low. These metal-plastic components could be designed, fabricated and integrated into an automotive structure within the framework of current automotive manufacturing practice, and would not compromise the performance of the vehicle.

8.2 COMPONENT SUBSTITUTION ANALYSIS

8.2.1 Methodology

An analysis was conducted to select suitable candidate parts for laminate application, to determine their weight and cost, and compare the results with that of the current components.

Previous vehicle teardown studies on a Chrysler Omni passenger car and a Ford F-150 pickup truck provided an available source

TABLE 8-2

SHEET METAL COMPONENTS ON 1978 OMNI SEDAN THAT COULD POTENTIALLY BE FABRICATED FROM METAL-PLASTIC LAMINATES

GENERAL APPLICATION	SHEET METAL AREA FT^2/CAR	STEEL SHEET METAL WEIGHT LB/CAR
EXTERNAL APPEARANCE PARTS	126	170
OTHER BODY PANELS	135	194
SEAT FRAMES	28	46
MISCELLANEOUS BODY PARTS	13	18
CHASSIS AND ENGINE APPLICATIONS	30	47
TOTAL ON-BOARD VEHICLE	332	475
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VEHICLE CURB WEIGHT		2,106

TABLE 8-3

SHEET METAL COMPONENTS ON 1980 FORD F-150 PICK-UP TRUCK THAT COULD POTENTIALLY BE FABRICATED FROM METAL-PLASTIC LAMINATES

GENERAL APPLICATION	SHEET METAL AREA FT^2/TRUCK	STEEL SHEET METAL WEIGHT LB/TRUCK
EXTERNAL APPEARANCE PARTS	250	399
OTHER BODY PANELS	166	239
SEAT FRAMES	18	33
MISCELLANEOUS BODY PARTS	31	69
CHASSIS AND ENGINE APPLICATIONS	65	98
TOTAL ON-BOARD VEHICLE	530	838
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VEHICLE CURB WEIGHT		3,687

TABLE 8-4

DISTRIBUTION OF SHEET USE ON REFERENCE VEHICLES

	CHRYSLER OMNI SEDAN DISTRIBUTION BASED ON		FORD F 150 TRUCK DISTRIBUTION BASED ON	
	AREA %	WEIGHT %	AREA %	WEIGHT %
EXTERNAL APPEARANCE PARTS	38.0	35.8	47.2	47.6
OTHER BODY PANELS	40.7	40.8	31.3	28.5
SEAT FRAMES	8.4	9.7	3.4	3.9
MISCL. BODY PARTS	3.9	3.8	5.8	8.2
CHASSIS AND ENGINE APPLICATIONS	9.0	9.9	12.3	11.7
TOTAL	100.0	100.0	100.0	100.0

TABLE 8-5

STUDY ASSUMPTIONS CONSTRAINING THE CHOICE OF AUTOMOTIVE COMPONENTS AS LIKELY CANDIDATES FOR NEAR-TERM USE OF METAL-PLASTIC LAMINATES

* CONSIDERED THE USE OF METAL-PLASTIC LAMINATES IN STIFFNESS LIMITED PARTS THAT WERE NOT:

- APPEARANCE PARTS
- SAFETY CRITICAL PARTS
- PARTS SUBJECTED TO SEVERE TEMPERATURE GRADIENTS
- PARTS WHERE MECHANICAL FASTENING IS CRITICAL

* STEEL FACED LAMINATES WITH 60 PERCENT CORE VOLUME RATIO ARE USED EXCEPT WHERE USE OF MINIMUM WEIGHT STEEL FACED LAMINATE (WITH 0.2 MM SKINS) WOULD RESULT IN WEIGHT GAIN, OR WHERE CORROSION CONSTRAINTS WOULD BE SEVERE. IN THESE INSTANCES, ALUMINUM FACED LAMINATES WERE CONSIDERED

* POLYPROPYLENE CORE LAMINATES ARE USED EXCEPT WHEN THE COMPONENT IS EXPOSED TO A FABRICATION TEMPERATURE OF 150°C (300°F) OR MORE OR AN IN-USE TEMPERATURE OF 120°C (250°F) OR MORE. IN THESE INSTANCES, NYLON CORE LAMINATES WOULD BE USED

* THE PRICE OF THE LAMINATE IS ASSUMED TO BE EQUAL TO THE COST OF CONTAINED MATERIALS PLUS $\$0.20/\text{FT}^2$ ($\$2.16/\text{M}^2$)

TABLE 8-6 PROPERTIES OF LAMINATES USED FOR DESIGN PURPOSES

DESIGNATION	S-P-S	S-P-S	S-P-S	S-P-S	S-N-S	S-N-S	A-N-A	A-N-
FACE SHEET MATERIAL	Steel	Steel	Steel	Steel	Steel	Steel	Aluminum	Alumi
CORE	(PP)	(PP)	(PP)	(PP)	Nylon 6-6	Nylon 6-6	Nylon 6-6	Nylon
LAMINATE THICKNESS, IN.	0.040	0.068	0.150	0.325	0.040	0.068	0.035	0.03
FACE SHEET THICKNESS, IN.	.008	0.0135	0.030	0.062	.008	0.0135	0.007	0.00
VOLUME PERCENT CORE	60	60	60	60	60	60	60	6
WEIGHT PER UNIT AREA, LBS./FT.^{2}	0.77	1.31	2.88	6.26	0.80	1.40	0.33	0.2
FLEXURAL STIFFNESS, 10^6 psi	21	21	21	21	21	21	7.8	7.8
FLEXURAL STRENGTH, 10^3 psi	33							
FLEXURAL FATIGUE STRENGTH, 10^3 psi	20	20	20	19				
TENSILE MODULUS, 10^6 psi	12	12	12	12	12	12	4	4
TENSILE STRENGTH, 10^3 psi	24	21	21	19				
TENSILE FATIGUE STRENGTH, 10^3 psi	14	14	14	14				
FORMING LIMIT DIAGRAM-FLD$_0$ PERCENT	33	30	36	47				
LIMITING DRAW RATIO	1.8	1.8	2.0	1.9				
DENT DEPTH @ 20 in-lb, in.	.073	.044	.021	.008				
STRESS RELAXATION CHARACTERISTICS PERCENT RETAINED AFTER SEVEN WEEKS (15.6 psi INITIAL)								
ROOM TEMP.	65	63	60	54				
150°F	63	60	58	41				
240°F	43	38	31	26				
MAXIMUM EXPOSURE TEMPERATURE IN FABRICATION, °F	270	270	270	270	440	440	440	440
MAXIMUM USE TEMPERATURE, °F	200	200	200	200	400	400	440	440
MAXIMUM AVAILABLE SHEET WIDTH								
CURRENT AVAILABILITY, in.	36	36	72	72	36	36	50	50
FUTURE AVAILABILITY, in.	48-72	48-72	72	72	48-72	48-72	60	60
COST OF LAMINATE								
\$ M^2	5.01	6.70	11.11	20.99	6.17	8.92	6.23	4.69
\$ ft^2	0.47	0.62	1.03	1.95	0.57	0.83	0.58	0.44
\$ lb	0.61	0.48	0.36	0.31	0.72	0.59	1.74	1.8

of parts and data for review and selection of candidates. (8-11, 8-12). A physical review of all Omni and F-150 parts was made to select the candidates for the cost-weight study. Restraints in the use of laminates discussed earlier in this report were used as a basis for the selection; i.e., high temperature, structural loading; etc. Other problems restricting the use of laminates are:

- Problems in fastening by screws, rivets, bolts, staking and serrated fittings.
- Inability to extrude the material for bearing surfaces.
- Not enough skin thickness to allow for material elongation in forming three corner deep draw areas.
- The thin skin also presents problems in embossing (stretching, sharp corners) finishing (sanding) and corrosion.

Table 8-7 presents a list of representative parts rejected as candidates for this study because of the above restraints. The variable costs of laminate parts and their steel counterparts were developed by the same methodology used in prior teardown studies and cost studies conducted by Pioneer (8-11, 8-12, 8-13). Briefly this methodology develops the cost by establishing each manufacturing operation required to produce the finished part and/or assembly. The associated labor/burden costs for each operation are developed and summed along with material costs to arrive at the final cost. These data do not include fixed costs such as: fixed burden, fixed labor, etc., which are included in total manufacturing costs.

Five (5) Omni parts and seven (7) F-150 parts were selected for the cost/weight analysis and the results are presented in Tables 8-8 and 8-9. The parts selected are internal to the vehicle (i.e. non-appearance parts) with relatively low levels of loading. Their designs do not contain any of the restraints discussed previously in this report, and appear to be the type of parts that the industry would select for initial laminate application. They are an assortment of assemblies and single parts. Most of these parts are made from cold rolled steel; however, there is one hot rolled steel part (Front Seat Frame) and two which contain aluminum (Hub Cap and Air Cleaner).

Tables 8-8 and 8-9 contain the part name, the number used per vehicle, finished weight, material designation, stock thickness, blank weight, blank cost, and the variable cost for both the current part and the unit made from a laminate material. These tables also contain a comparison between the current part and the laminate substitute in terms of weight savings, differences in variable costs and the cost per unit weight saved.

8.2.2 Design Considerations

Substituting one material for another most often requires some design changes in order to accommodate the peculiarities of

TABLE 8-7

MANUFACTURING RESTRAINTS

LAMINATE MATERIALS

	Re-Strike	Extruded Bearing Surface	Serrated Fittings	Mechanical Fasteners-Rivets, Bolts, Sheet Metal, Screws, etc.	Material Elongation (Stretch)	Metal Finish	Warping (Paint Cycle)	Spring Stop	Bearing Surface	Hot Upset & Mech. Staking
Door Latch Mech.	X	X		X	X			X	X	X
Hood-Outer						X	X			
Window Regulator	X	X	X	X					X	
Master Cyl. Cover	X				X					
Cowl					X		X			
Fender-Outer				X		X	X			
Fender-Inner				X	X					

TABLE 8-8

CANDIDATE PART COST/WEIGHT ANALYSIS – 1978 OMNI

LAMINATE STUDY

	CURRENT PART						LAMINATE SUBSTITUTE					PER VEHICLE		
PART DESCRIPTION	FIN. WGT. (lb.)	MATL. (1)	BLANK COST ($)	BLANK WGT. (lb.)	VARI. PIECE COST ($)	USAGE	FIN. WGT. (lb.)	MATL. (2)	BLANK COST ($)	BLANK WGT. (lb.)	VARI. PIECE COST ($)	Δ WT # -	Δ $ +	COST/LB SAVED
<u>OMNI PARTS</u>														
RR SEAT BACK PNL	15.22	.035 CRS	4.46	17.44	7.80	1	9.07	.040 SPS	8.54	14.00	12.83	6.15	5.03	.82
HOOD PANEL INNER	15.25	.035 CRS	7.63	30.5	10.43	1	7.74	.040 SNS	11.15	15.48	13.92	7.51	3.49	.46
LIFTGATE INNER	5.20	.033 CRS	6.45	25.8	10.50	1	2.9	.040 SNS	10.37	14.4	14.63	2.3	4.13	1.80
DOOR PANEL INNER-FT	6.94	.030 CRS	2.89	11.56	6.86	2	4.23	.040 SNS	5.14	7.05	9.14	5.42	4.56	.84
DOOR PANEL INNER-RR	4.46	.030 CRS	2.25	8.92	6.22	2	2.73	.040 SNS	3.92	5.45	7.92	3.46	3.40	.98

(1) CRS = Cold Rolled Steel
(2) SPS = Steel Polypropylene Steel
SNS = Steel Nylon Steel

TABLE 8-9

CANDIDATE PART COST/WEIGHT ANALYSIS - 1980 F-150 PICK-UP TRUCK.

LAMINATE STUDY

	CURRENT PART						LAMINATE SUBSTITUTE					PER VEHICLE	
PART DESCRIPTION	FIN. WGT. (lb.)	MATL. (1)	BLANK COST ($)	BLANK WGT. (lb.)	VARI. PIECE COST ($)	USAGE	FIN. WGT. (lb.)	MATL. (2)	BLANK COST ($)	BLANK WGT. (lb.)	VARI. PIECE COST ($)	Δ WT # - Δ $ +	COST/LB SAVED
F-150 PARTS ENG. AIR CLNR.	3.28	.030 AL .030 CRS	2.34 .44	2.34 1.74	See Laminate	1	2.40	.035 ANA .040 SNS	3.20 82	1.84 1.13	Δ +1.24	.88 1.24	1.41
GRILLE BRKT-RT&LT	1.07	.032 CRS	.34	1.34	See Laminate	1	.62	.040 SPS	.48	.78	Δ +.14	.45 .14	.31
TORQUE CONV ACCESS PLT	.46	.037 CRS	.13	.51	See Laminate	1	.23	.040 SPS	.15	.25	Δ +.03	.23 .03	.13
FRONT SEAT FRAME	19.17	.044/ .053 HRS	5.33	21.31	22.97	1	9.59	.060 SPS	5.12	10.66	24.32	9.59 1.35	.14
FLOOR PAN ACCESS HOLE COVER	.27	.036 CRS	.07	.28	See Laminate	2	.14	.040 SPS	.09	.15	Δ +.02	.26 .04	.15
FRONT BRAKE DUSTSHIELD	1.06	.028 CRS	.44	1.74	See Laminate	2	.71	.040 SPS	.71	1.16	Δ +.27	.70 .54	.77
HUB CAP	.49	.025 AL	.63	.63	See Laminate	4	.33	.030 ANA	.78	.43	Δ +.16	.64 .61	.95
					*48x62 SHEETS REQUIRED								

(1) AL = Aluminum, CRS = Cold Rolled Steel, HRS = Hot Rolled Steel

(2) SPS = Steel-Polypropylene-Steel, ANA = Aluminum-Nylon-Aluminum, SNS = Steel-Nylon-Steel

the new material. The following is a discussion relative to design changes required in order to fabricate the part out of laminate material:

8.2.2.1 Omni Components - (See Table 8-8)

Panel - Rear seat back inner: This assembly is currently made of cold rolled steel and is composed of six separate pieces. These six pieces are spot welded to the outer panel. Figure 8-1 is a sketch of the inside view of the panel showing the orientation of the parts. Parts (2), (3), (4) and (6) are replaced with a laminate material part. Parts (1) and (5) support the rear seat pivot points, part (7) is the back of the rear seat and contains provision for latching and must survive impact loads.

As a laminate, this inner panel will be a rectangular ring representing parts 1 thru 6. Part 7 will be made of one piece and the center will be offal, as shown on Fig. 8-1 as the shaded area. Parts 1 and 5 will remain, made of steel, to support the hinge pins. These parts will be resistance welded to the outer panel and the one piece inner panel will be bonded over them. Part 7, the outer panel, remains steel to take the impact loads as it functions as the rear deck.

Discussions were held with bonding engineers relative to the number of joints in the inner panel assembly. It was the consensus that, for the most durable design, the area covering Parts (2), (3), (4) and (6) would be made from one piece with a hemming operation at the steel hinge supports. The steel parts (1) and (5) would remain steel and be bonded to the laminate part while being resistance welded to the steel back outer panel (7). This arrangement appears to be the most structurally sound configuration for substituting laminate material under current technology.

A consequence of this design change is that the substitute laminate part has a greater amount of offal than the current part made from steel. This accounts for a different ratio of blank weight to finish weight for this component than the ratio found in other parts considered in this analysis.

It should be noted that the current part "variable cost" includes the cost of fabricating parts (2), (3), (4) and (6) plus the complete rear panel assembly costs. The laminate substitute "variable cost" includes the fabricating cost of the laminate part (replacing parts (2), (3), (4) and (6) plus the complete rear panel assembly costs (containing the laminate substitute). Fabrication costs of parts, used in both approaches (i.e. (1), (5) and (7)) are not included.

Hood panel - inner (reinforcement): The inner hood panel consists of the panel, hinge reinforcements and the lock striker as shown in Figure 8-2. The hinge reinforcements and the lock striker were not costed because they remain the same in either

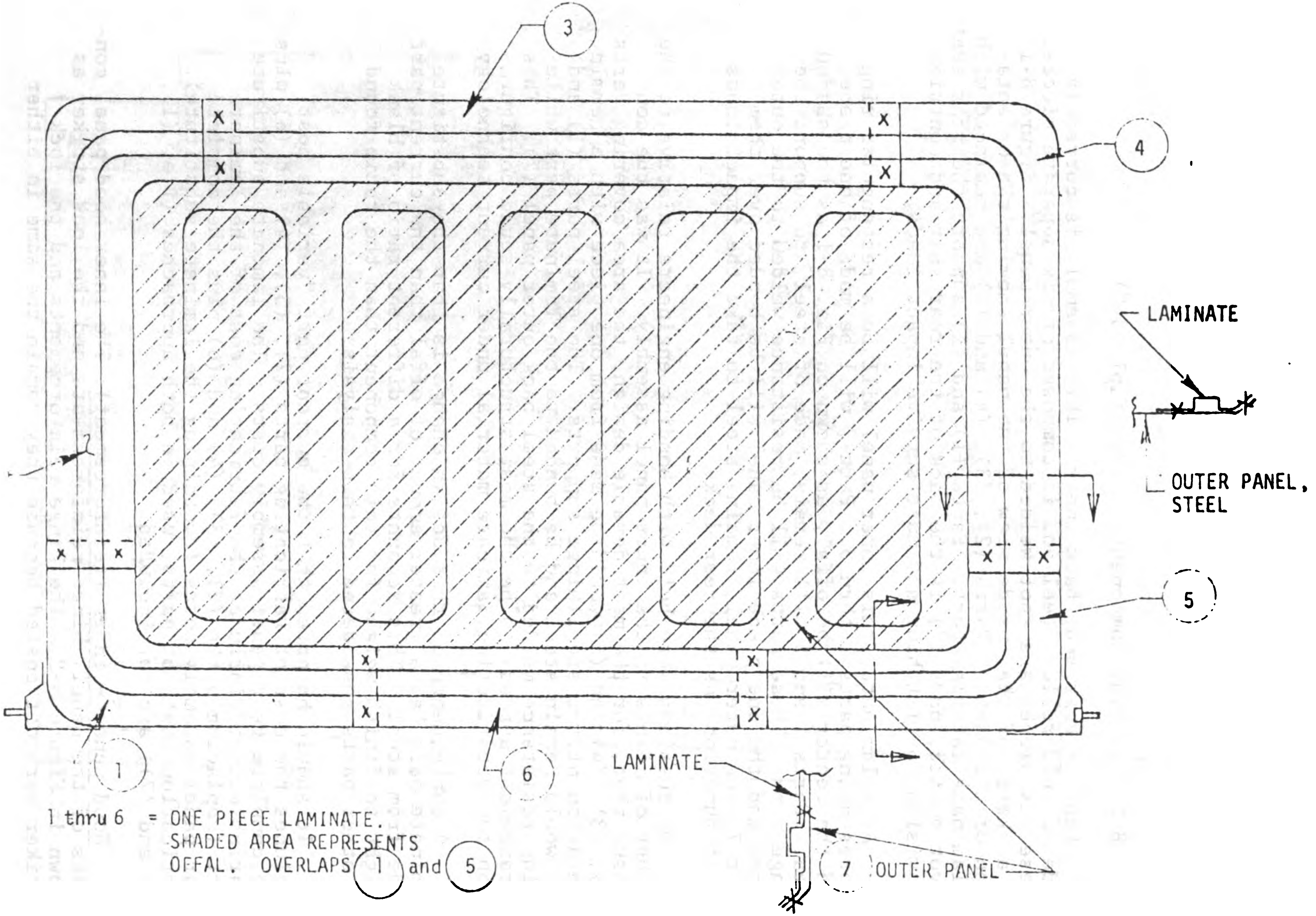


Figure 8-1 1978 OMNI Inner & Outer Rear Back Panel

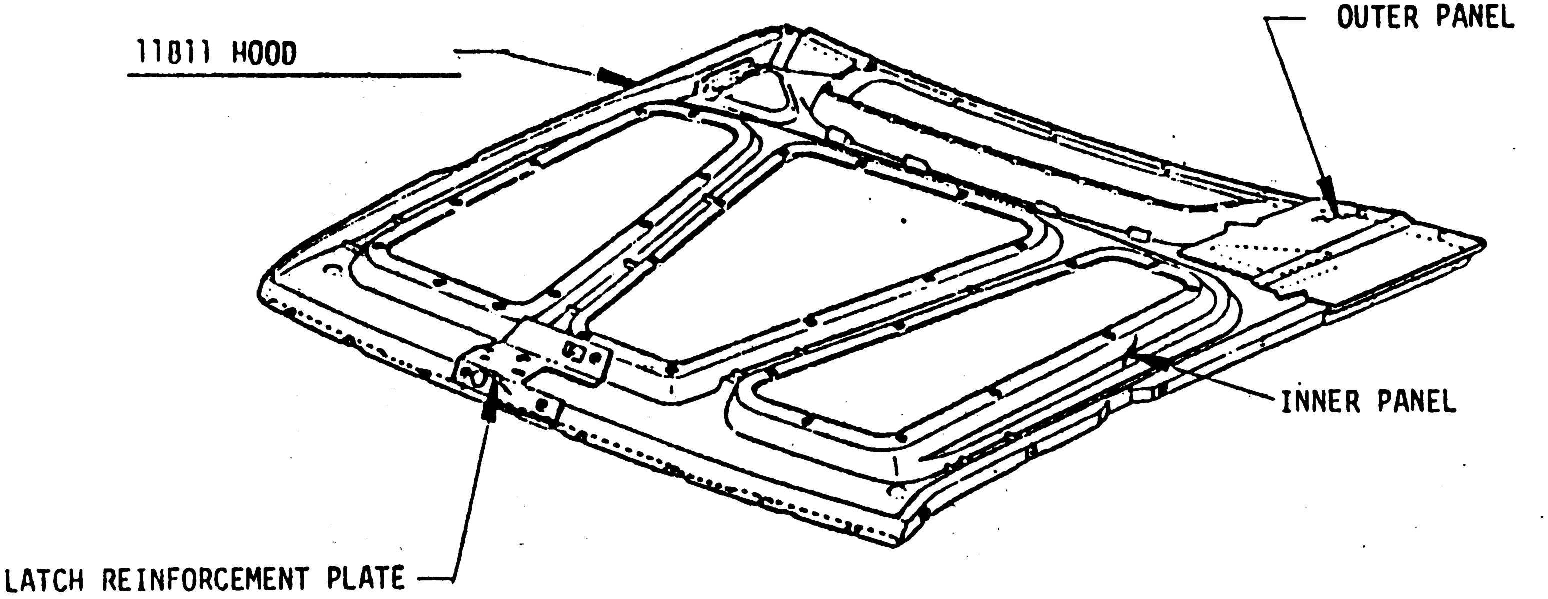


Figure 8-2 1978 OMNI Hood Panel - Reinforcement case. The design of the inner panel does not change with the use of laminates.

In the "all" steel design, the inner and outer panels are flanged but not hemmed. They are adhesive bonded in the horizontal plane and spot welded in the vertical plane (on the flanges). The "laminate inner panel" concept utilizes adhesive bonding in the same areas as the steel inner to steel outer approach; however, the "stitching" is used in the vertical plane instead of spot welding. Stitching is a process whereby an area approximately .060 in. wide and .375 in. long is lanced into a shallow "V" after the parts have been assembled. Stitching is commonly used in the sheet metal bonding of parts.

Steel-nylon-steel laminate is used to withstand the high temperature of exposure of the paint curing cycle. Passage through the paint bake oven is also used to cure the adhesive.

The "variable cost" for the current part includes the cost of fabricating the inner steel panel (only) plus the assembly costs of the complete assembly. The "variable cost" for the laminate substitute includes the fabrication costs of the laminate inner panel plus the assembly costs of the complete assembly.

<u>Panel - liftgate inner</u>: The current liftgate consists of steel inner and outer panels, lift support reinforcements, hinge reinforcements and a latch reinforcement assembly as shown in Figure 8-3. The reinforcements are resistance welded to the inner panel in the current design. The inner and outer panels are resistance welded at the window flange and hemmed, and arc welded at four places around the outer periphery.

The concept utilizing a "laminate" inner panel utilizes the same steel reinforcements; however, they are bonded to the laminate material. It is assumed that the bonding material and bonding application specifications are such that the "bonded joints" meet the structural requirements of the application.

The laminate inner panel is adhesive bonded and hemmed to the outer panel. Arc welding used in the "all" steel assembly is difficult with laminate materials because of the thin skin, and is not included in this concept.

Steel-nylon-steel material is used because of the paint cycle temperatures. Consequently, residence in the paint bake oven is used to cure the adhesive material.

As in the case of other assemblies in this study, the current part "variable cost" includes the fabrication cost of the steel inner panel and the total assembly costs of the liftgate. The laminate part costs consist of the fabrication costs of the laminate inner panel, and the total assembly costs of the liftgate assembly.

11A9 - DECK LID & TAIL GATE

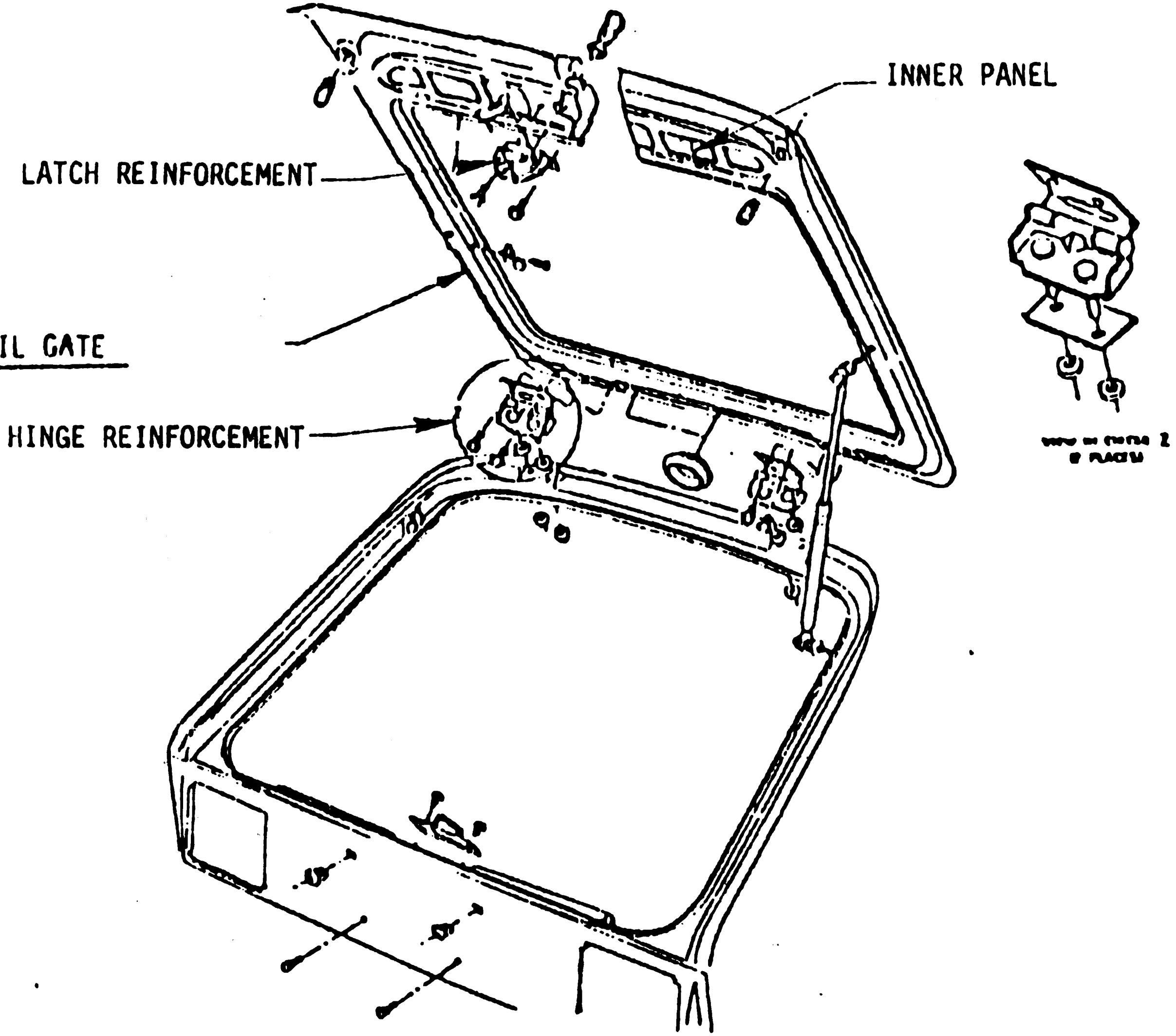


Figure 8-3 1978 OMNI Lift Gate

Door panel - inner front, inner rear: The inner panels on both doors consist of two pieces, the inner panel and the inner extension as shown in Figures 8-4 and 8-5. The inner extension is made of heavier material (.060 in.) and the hinges are arc welded to it. The door impact reinforcement is resistance welded to the inner extension on one side and the inner panel on the other. The door lock reinforcement is resistance welded to the inner panel. The inner panel, inner extension and the outer panel are hemmed and welded on three sides; at the top, the inner and outer panels are resistance welded at matching flanges at one side of the window well. The window frame is resistance and arc welded to the inner panel on one side, and the extension on the other.

In the laminate concept, the laminate material is substituted for the inner panel only, all other parts are made of steel including the inner extension. The door impact reinforcement beam is welded to the inner extension on one side and to the outer panel on the other side. The impact reinforcement is extended into the rolled over flange of the outer panel and hemmed. The latch (lock) reinforcement is changed so that it is welded to the impact reinforcement. The laminate inner panel is bonded to the inner extension on one side and hemmed and bonded on the panel and impact beam in other areas. The hem is resistance welded only in the areas of the inner extension and the impact reinforcement. The window frame is welded to the inner extension and bonded to the laminate inner.

The variable cost for the current part includes the fabrication cost of the steel inner panel, and the total door assembly cost. The variable cost for the laminate part includes the fabrication cost of the laminate and the total door assembly cost.

8.2.2.2 Ford F-150 Pickup - Truck Components - (See Table 8-9)

Engine air cleaner: The existing air cleaner consiste primarily of the housing and the fresh air intake tube as shown in Figure 8-6. The housing is .030 in. aluminum and the tube is .030 in. low carbon steel. The tube is riveted to the housing.

As a laminate assembly the housing is drawn from .035 in. ANA (Al-Nylon-Al) and the tube is made of .040 in. SNS (Steel-Nylon-Steel). They are adhesively bonded together. Nylon core laminate was chosen because the part is over the engine block and is thus exposed to elevated use temperatures.

Both current and laminate part "variable cost" include fabrication and assembly costs.

Grille bracket: The grille is supported at three points. At the center is a bracket which supports the hood lock and is therefore made of heavier material than the two outboard brackets. The outboard brackets are mirror images of each other and serve only to support the grille. They are bolted in position and in

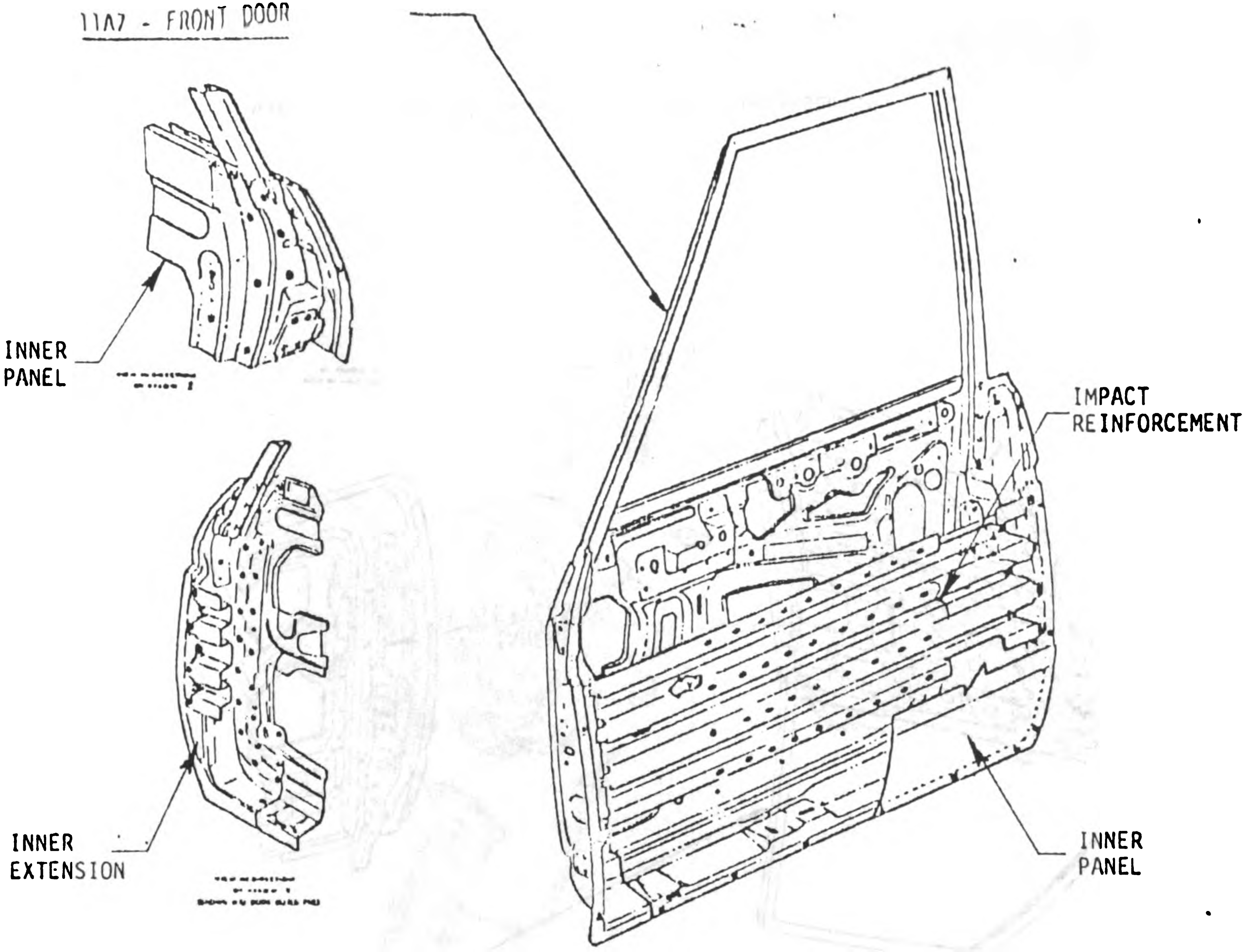


Figure 8-4 1978 OMNI Front Door - Complete Assembly

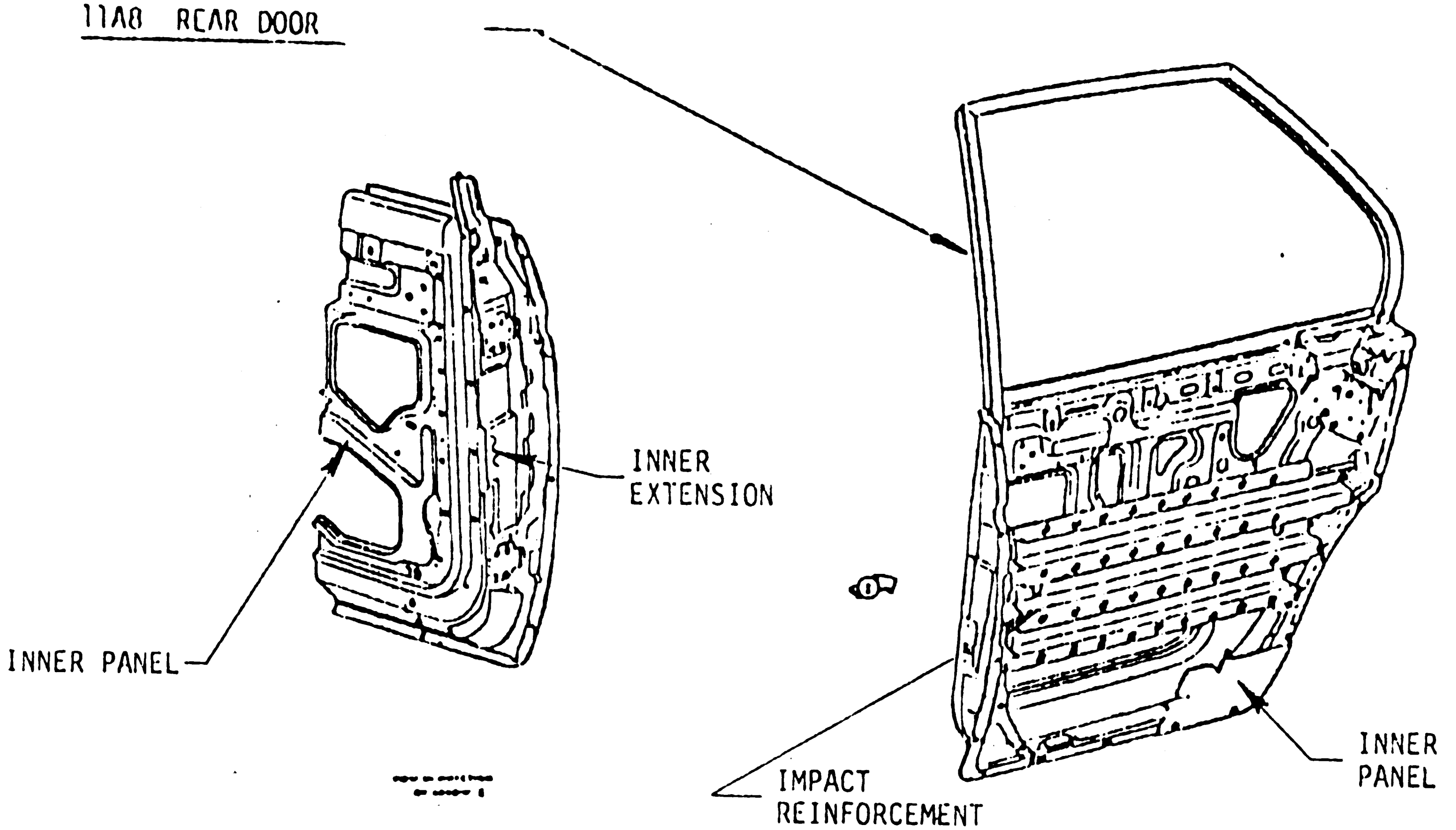


Figure 8-5 1978 OMNI Rear Door - Complete Assembly

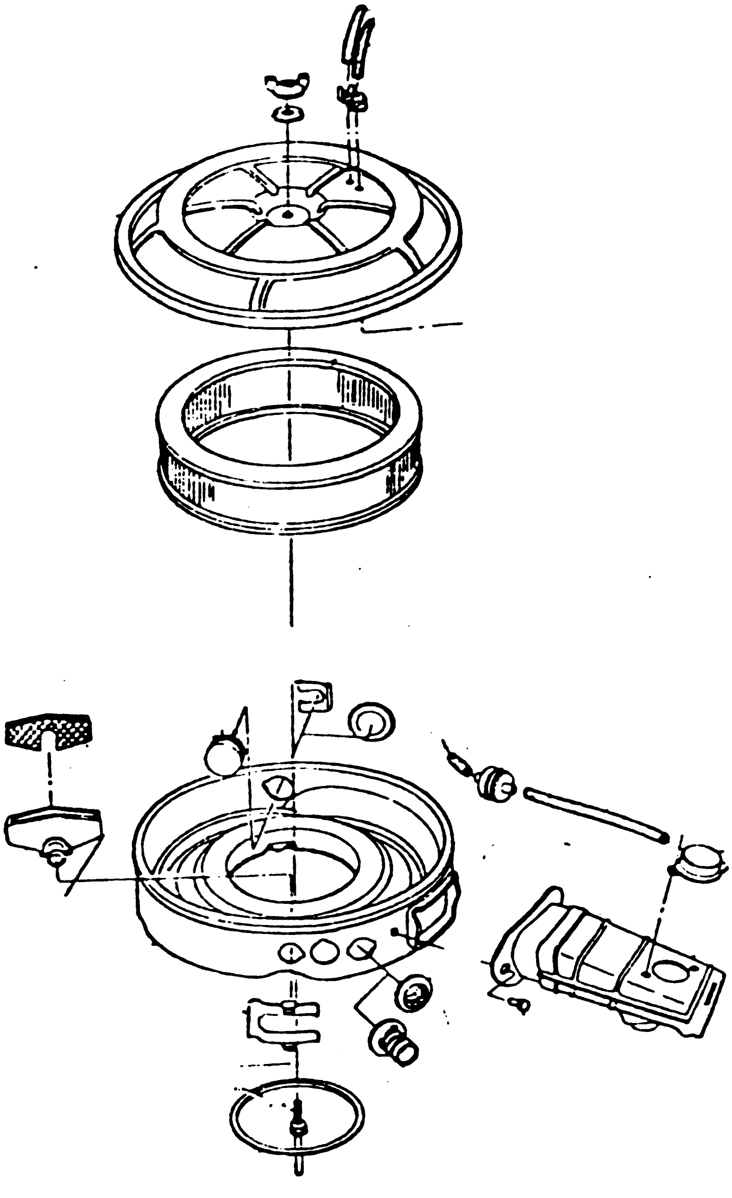


Figure 8-6 1980 Ford F-150 Engine Air Filter turn the grille is bolted to them.

The center bracket was not selected as a candidate for this study because of the strength required to support the hood lock. The outboard brackets were analyzed as potential candidates. The possibility that the laminate will creep under the tension of the bolts is the only potential shortcoming of this laminate application. Figure 8-7 shows this component. The costs are only for fabrication.

Torque convertor access plate: This is a straight forward substitution of laminate for low carbon steel. As shown in Figure 8-8, there is a very shallow bead in the part. It is bolted to the bell housing.

The only problem may be the creep in the laminate resulting from the bolted connection.

The costs are only for fabrication.

Seat Frame: As shown in Figure 8-9, the seat frame consists of five primary sheet metal parts plus reinforcements, nuts, stops, and cross members. One of the two parts forming the back section of the frame is stamped such that tabs are formed to support the seat springs. The shape of the tabs is such that they must resist bending in supporting the springs. It was the consensus that the laminate could not withstand the bending load; therefore, this element was not costed.

The second element of the back of the frame serves to make that section more rigid. It was costed as a laminate; the two sections being bonded together.

The front member supports the springs with tabs that are slanted away from the spring load. The bending load is minimized and the tabs are primarily in shear. This element was costed as a laminate.

The two side members were costed as laminates; the entire assembly of primary elements was costed as adhesively bonded.

As sheet metal, all of the elements required reinforcements, for seat track and back attachment. Extra heavy stampings were used for the back stops. When costed as laminates, it was necessary to bond these reinforcements. The backstops were welded to the one back element that was not substituted.

The cross-members were not substituted because it was felt that the laminate could not take the loading.

Each side element in the original design has a knot welded to a reinforcement which is welded to the side member. The knot to reinforcement design is used in the laminate with the reinforcement and bonded to the laminate side member.

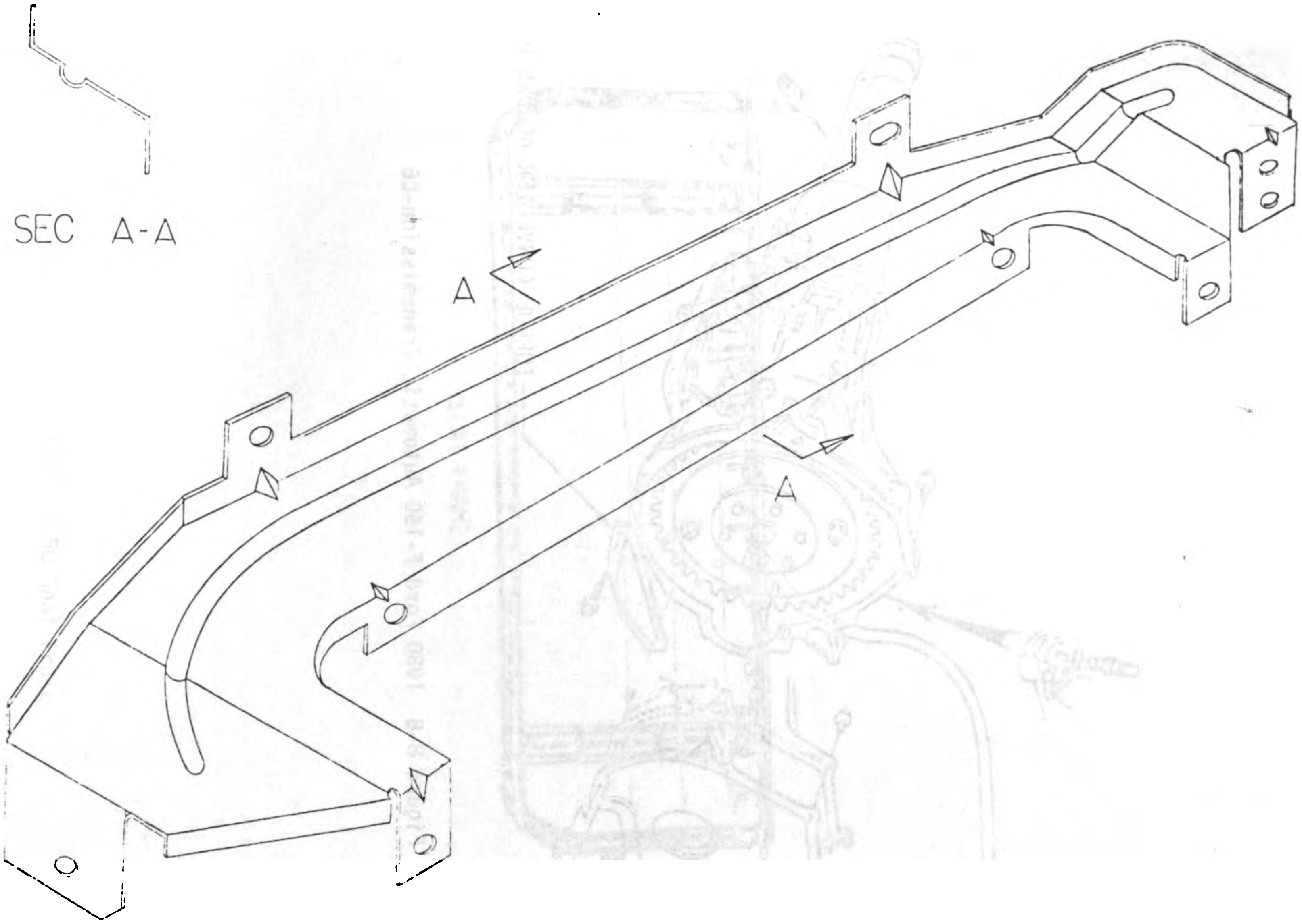


Figure 8-7 FORD F-150 Grille Bracket

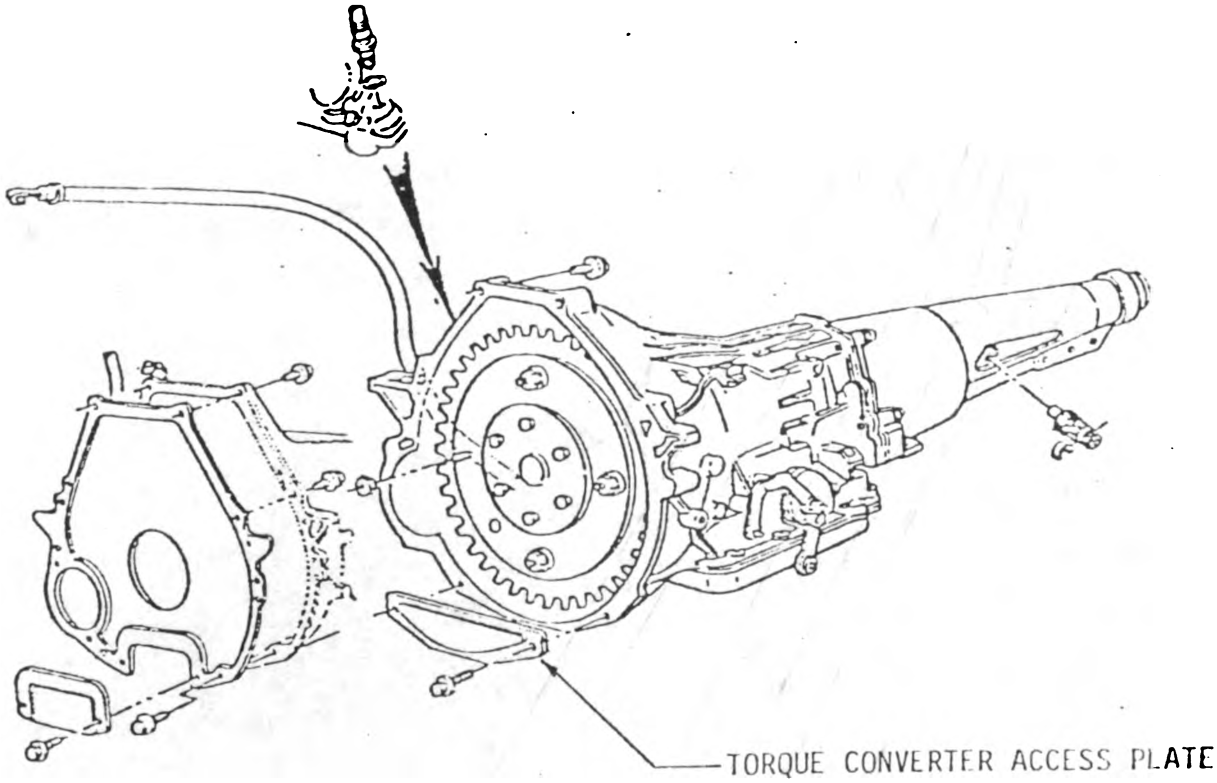
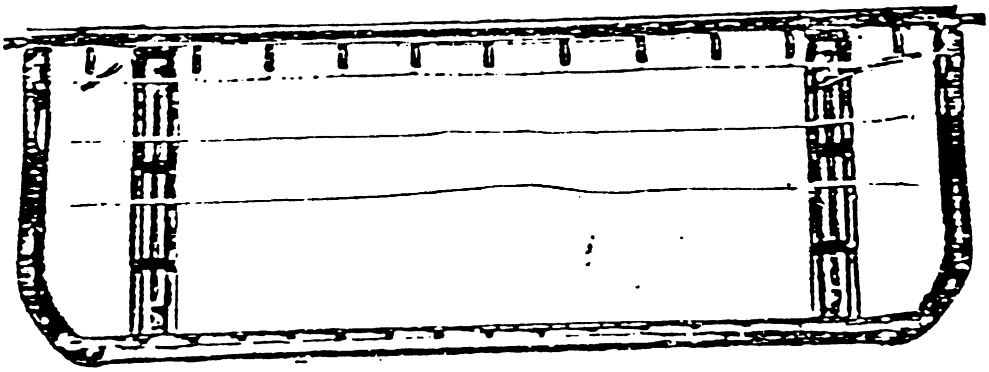


Figure 8-8 1980 Ford F-150 Automatic Transmission-C6



SEAT FRAME

Figure 8-9   1980 FORD F-150 Seat Frame

Floor pan access hole cover: This is a simple replacement of laminate for a galvanized low carbon steel stamping. The bolting pressure and resulting creep in the laminate is a potential problem.

As shown in Figure 8-10, the steel part has a reverse draw to give it rigidity. The laminate part was costed with the same form but the increased rigidity of the material may permit the elimination of the draw.

Costs reflect fabrication only.

Front brake dust shield: The dust shield is a stamping with a moderate drawn section, as shown in Figure 8-11. It is well within the capability of the laminate material. Bolting pressure and subsequent creep of the laminate may pose a problem.

The current dust shield is made from .028 in thick steel; however, .040 in. thick laminate material was used as the substitute in this analysis because this is the thinnest steel-polypropylene steel laminate available.

The costs are only for fabrication.

Hub cap: The existing part is made of .025 in. aluminum and has relatively deep draw with a mounting bead curled at the opening as shown in Figure 8-12. The laminate part was costed per the same process as the original part; the assumption was made that the curl for the bead would form in the laminate in a near identical fashion as the sheet metal.

As in all other single part applications, the cost is for fabrication only.

8.2.3 Cost Per Pound of Weight Saved

A review of the COST/LB SAVED column in Tables 8-8 and 8-9 shows that there is a relatively large difference from component to component irrespective of whether they are assemblies or single parts. A review of the design and manufacturing processes reveal the following reasons for the differences:

- Laminate materials can be formed into most part shapes with the same fabrication processes used to form steel and aluminum parts. Consequently, for those applications where laminate materials can be feasibly substituted for steel or aluminum, the fabrication cost will be the same for both cases. The cost per pound saved is, therefore, mainly a function of the differential in material cost between the two parts, as indicated graphically in Figure 8-13.

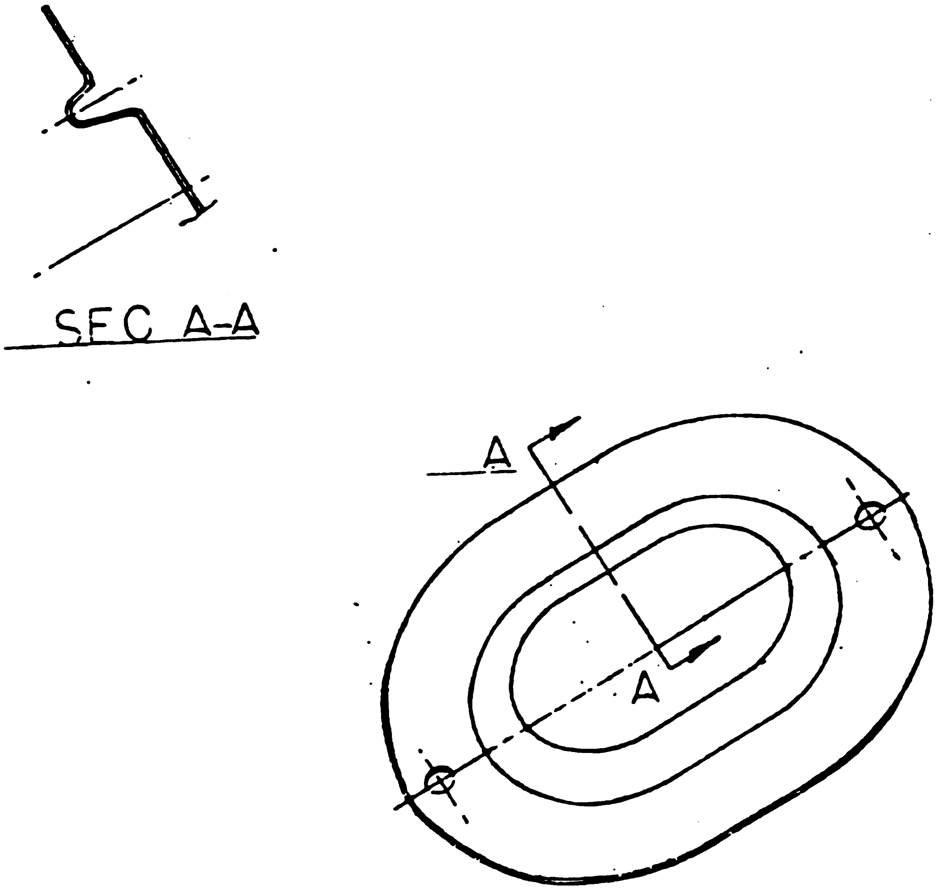


Figure 8-10 1980 Ford F-150 Floor Pan Access Hole Cover

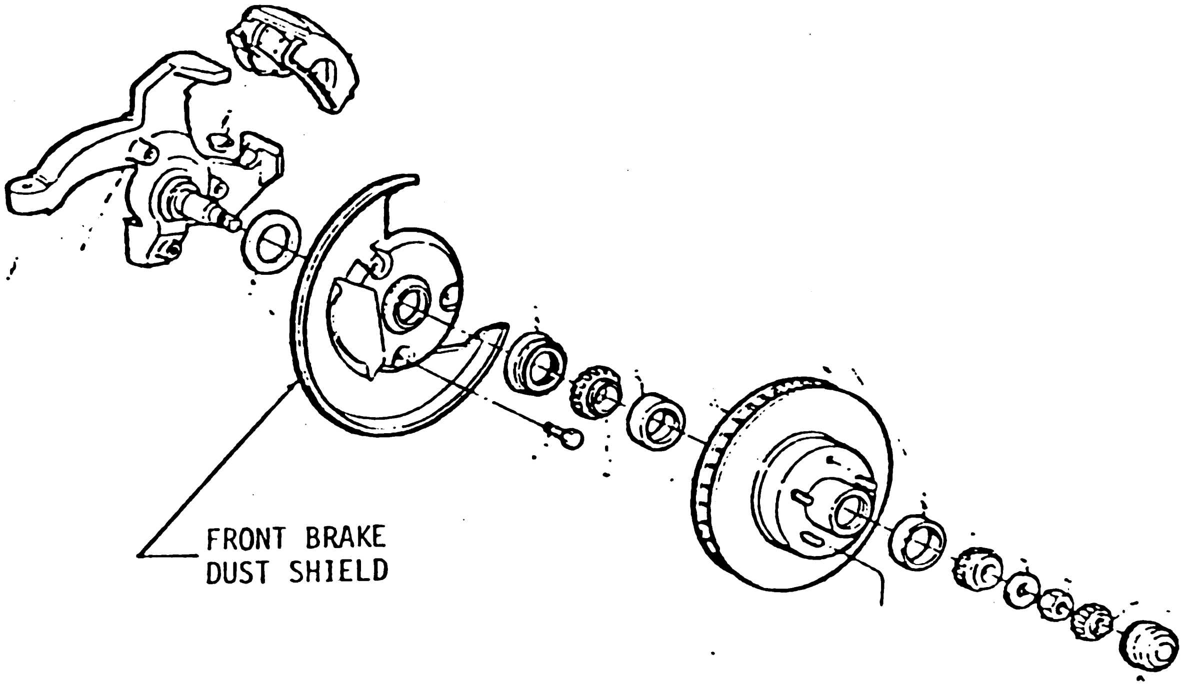


Figure 8-11 1980 Ford F-150 Partial Disc Brake Assembly

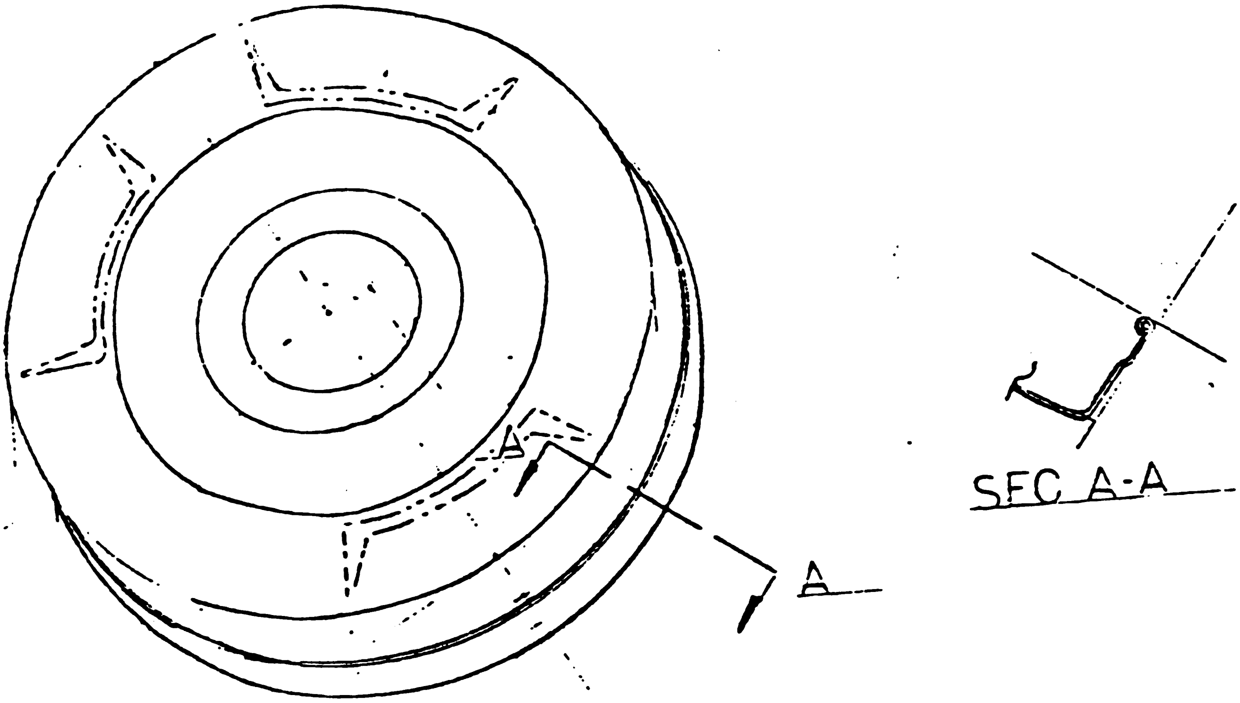


Figure 8-12 1980 Ford F-150 Hub Cap

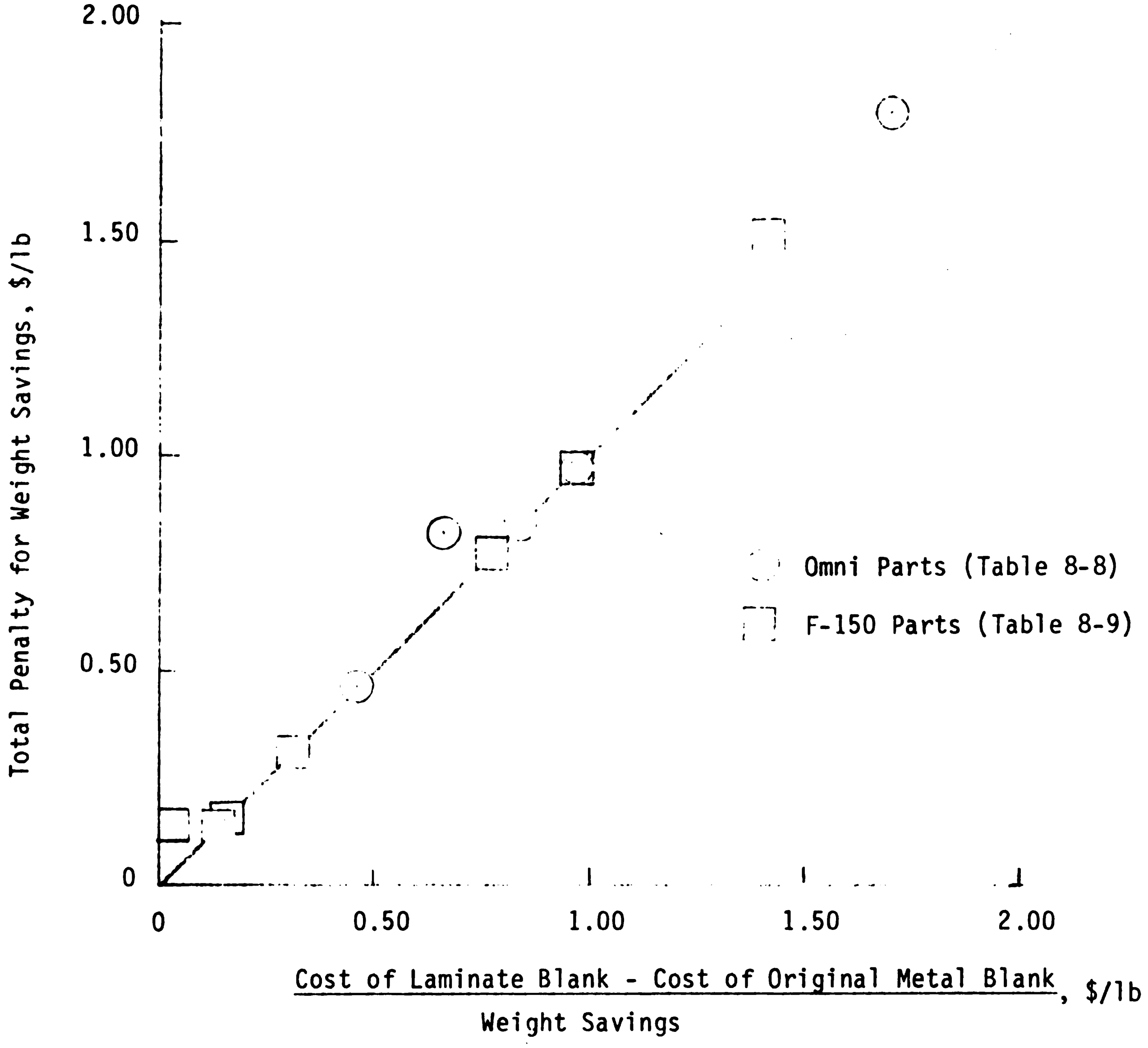


FIGURE 8-13. CONTRIBUTION OF MATERIAL COSTS INCREASE TO THE OVERALL COST PENALTY FOR LAMINATE SUBSTITUTION.

- The cost penalty for weight savings increases with the offal rate. If the offal rate is high, the penalty for weight savings will be high. The material costs to the manufacturer are based on the cost of the purchased material blank. Net material costs increase as the utilization of the blank decreases. Since the unit cost of laminate, either on a unit area or unit weight basis, is higher than the cost of sheet metal (usually steel), high offal rates will magnify the cost differences between the laminate and the original sheet metal, and thus increase the differential in material costs. This trend is indicated in Figure 8-14, which is a plot of the total cost penalty for weight savings for the different components of the Omni and F-150 that were examined against the ratio of the unit cost of the laminate blank times the ratio of the weight of the laminate blank to the weight of the finished laminate part. This ratio is the inverse of the laminate utilization efficiency which is also equal to one minus the offal rate. This plot, which neglects the cost of the base line materials, indicates that the cost penalty per pound of weight saved on the vehicle increases with the unit cost of the laminate blank and with the offal rate.

- Replacing thin aluminum sheet with an aluminum-nylon-aluminum laminate results in a fairly high cost penalty for weight savings, as can be noted from the F-150 air cleaner and hub cap. This follows from two factors. First, the difference in density between aluminum and aluminum-nylon aluminum laminate is relatively small so that the amount of weight that can be saved is small. Secondly, since the aluminum-nylon-laminates that are being substituted are very thin, the laminate fabrication costs are a significant part of the total cost of the laminate, making the unit material cost of the laminate high. The combination of the two factors results in a high cost penalty per pound of weight saved.

8.3 IMPLICATIONS FOR LAMINATE USE

As indicated in Table 8-10, the general consensus of the automotive industry is that weight savings is of value to the industry, and that this value will increase from about $0.50/lb ($0.90/kg) currently to possibly three times this value by the end of the decade. These figures are in general agreement with calculated values based on the cost penalty to a manufacturer of not meeting the mandated AFER (Automotive Fuel Economy Regulation) Standard in a given year, or in terms of the discounted value of the fuel saved by a consumer over the lifetime of a vehicle (8-15).

For a number of the F-150 parts listed in Table 8-9, replacement of sheet steel with metal-plastic laminates would result in a cost penalty of significantly less than $0.50/lb. These include

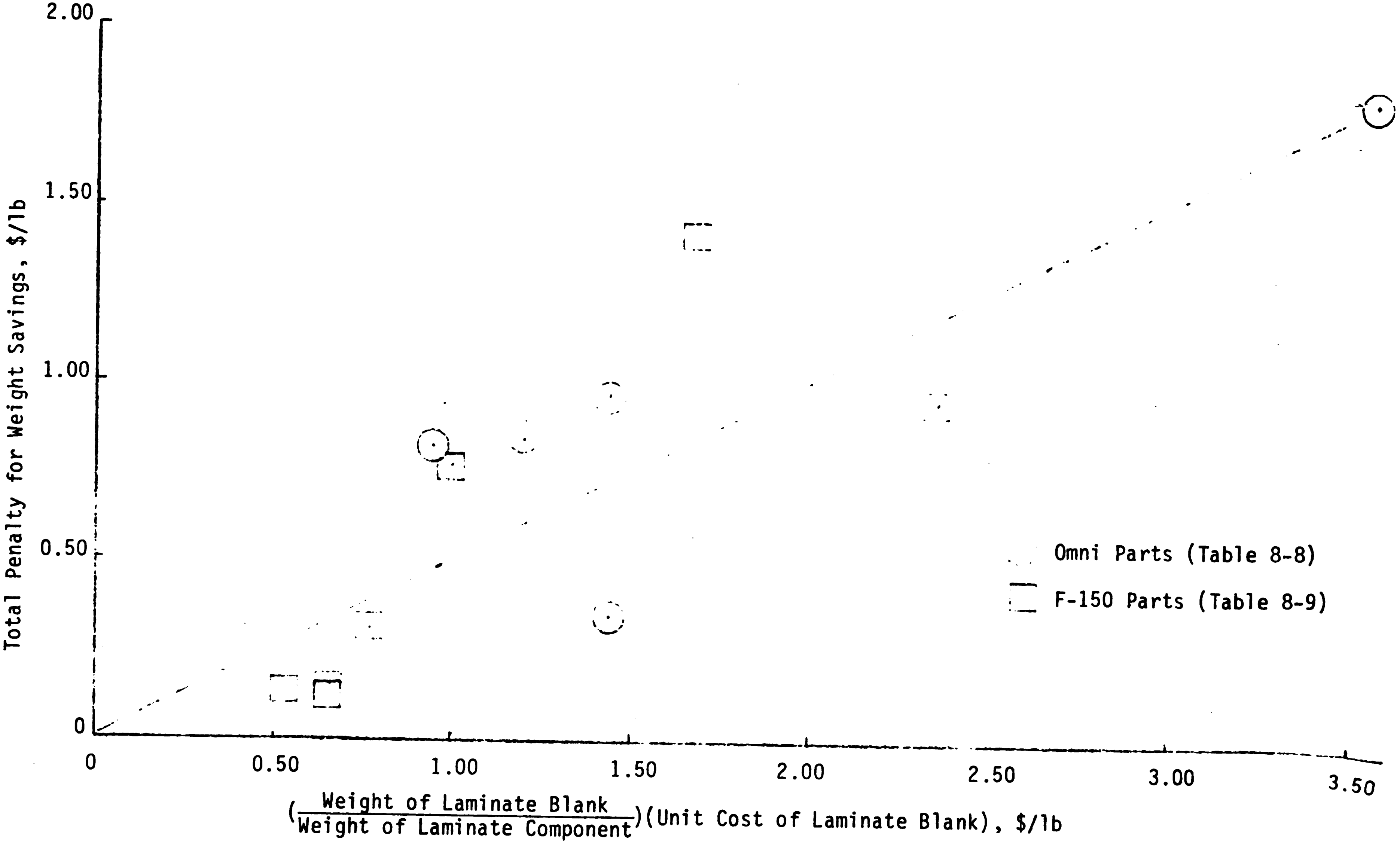


FIGURE 8-14. EFFECT OF RAW MATERIALS COSTS AND UTILIZATION ON COST PENALTY FOR WEIGHT SAVINGS

TABLE 8-10

DELPHI FORECAST OF THE VALUE OF FUTURE WEIGHT SAVINGS

YEAR	1979	1985	1990
	Value of Weight Savings ($/lb) ($/kg)		
Technologists	0.90 (1.98)	1.00 (2.20)	1.25 (2.75)
Marketing Manufacturers	0.50 (1.10)	1.00 (2.20)	1.13 (2.49)
Marketing Suppliers	0.50 (1.10)	1.00 (2.20)	1.50 (3.30)

SOURCE: Reference 8-14

the grille brackets, the torque converter access plate, the floor pan access hole cover and the front seat frame. For these components, both the feasibility and the economics of metal-laminate substitution are favorable. They thus would be prime candidates for future initial production use of metal-laminates. If all these components of the F-150 were made of laminate, the total weight savings would be 10.53 lbs. (4.8 kg), at a cost increase of \$1.56 for an average cost penalty of \$0.15/lb (0.33/kg). The seat frame represents the predominant use of laminates in this instance.

The cost penalty for the other three components identified in this Table is significantly higher than the above, but still less than \$1.50/lb (\$3.30/kg). In specific situations, especially in the latter part of the decade, these components might possibly be made of laminates.

As indicated in Table 8-8, the cost penalty for weight savings for the Omni parts that were examined ranges from \$0.46/lb (\$1.01/kg) to \$1.80/lb (\$3.96/kg). Only the hood inner panel is marginally below the \$0.50/lb (\$1.10/kg) use figure established above. On that vehicle, it would represent the first use of laminates among the various parts analyzed. The door inner panels and rear seat back panel have cost penalties of \$0.80/lb (\$1.76/kg) and \$1.00 (\$2.20/kg) which would make them less likely candidates. The juxtaposition of the door inner panel and of the door anti-intrusion beam, a safety critical part, might discourage an auto designer from using a metal-plastic laminate for the door inner panel until a better data base were obtained. The high cost penalty of weight savings for the liftgate inner panel, which has a very high manufacturing scrap rate, makes this component an unlikely application of metal-plastic laminates.

In closing, it is to be noted that the costs indicated for the laminates were based on introductory costs. As the technology matures, the costs of the laminates (in constant dollars) may well be less than those used in these calculations, if the laminating costs assumed were 12.5¢/ft^2 instead of 20¢/ft^2, the cost of 0.040 in S-P-S laminate would be reduced by 16 percent, and the cost of S-N-S laminate would be reduced by 13 percent. In both cases, the least favorable cost was assumed for the polymer. Use of talc-filled polypropylene homopolymer with an adhesive would have reduced the cost of S-P-S- by about 2¢/ft^2 6 percent, with a 4 percent loss in weight reduction. Assuming the lower value for the range of material costs presented in Table 7-5 for S-N-S laminate instead of the higher value assumed, would reduce the presumed cost of S-N-S laminates by about 10 percent. This could also apply to the A-N-A laminates. These cost chnages would improve the competitive position of metal-plastic laminates, and enhance the probability of their use. These cost changes imply a more mature industry which would not exist for a number of years.

CHAPTER 8 REFERENCES

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9.0 CURRENT STATUS OF METAL PLASTIC LAMINATES

9.1 INTRODUCTION

This section will review the current status of metal-plastic laminate technology in terms of the potential application of the technology to automotive applications. This discussion is based on the interviews the principal investigator carried out during the course of this study with various participants as outlined in Table 1-1. These participants are both potential suppliers and potential users of laminates that currently have active development programs in this area. The suppliers included polymer manufacturers, steel producers, aluminum sheet producers, and coil coaters. Potential users include vehicle manufacturers and component manufacturers.

9.2 POLYMER SUPPLIERS

The polymer suppliers are the most enthusiastic promoters of metal-plastic laminates at the moment. Among the various groups surveyed, they appear to have devoted the largest budgets to this technology, and have the resources and commitment to support the long-term research and development programs that still will be required to bring metal-plastic laminates to commercial fruition. This enthusiasm is due to the fact that, for the polymer manufacturers, automotive use of metal-plastic laminates would create a very large, totally new market for their products in terms of polymers for the cores or the adhesives.

Polymer suppliers that currently have an active interest in metal plastic laminates include:

- U.S. Firms

    Arco Chemicals Co.
    Dow Chemical USA
    Hercules Inc.
    Monsanto Corp.
    Morton Chemical Co.
    Phillips Petroleum, Inc.
    U.S. Steel Corp.

- Foreign Firms

    BASF AG
    Mitsui Petrochemicals Inc.
    Solvay & Cie

9.2.1 Arco Chemicals Co.

Arco is currently exploring the potential market for aluminum high density polyethylene laminates, as well as aluminum polypropylene. Arco is a manufacturer of both polymers; and a subsidiary, The Anaconda Company, is a producer of sheet aluminum. Steel faced laminates are also being evaluated as alternate systems. Arco has initiated some laboratory work, but is not yet in a position to release data or samples for evaluation. The temperature resistance of the polyolefin laminates is of concern.

9.2.2 Dow Chemical Company

Dow Chemical Company appears to have a fairly significant research effort underway. The current effort of interest is focused on steel-polyethylene-steel laminates, and is based on work performed in related areas that has been carried out at Dow over the past 15 to 20 years. The focus on steel polyethylene laminates is based on the low cost of these raw materials. Some work is also being carried out with aluminum faced laminates, in part because of their greater weight reduction potential, but also, in part, because of concern about the future price of steel products. According to one Dow representative, the present price of steel is below the price that would be justified in terms of the capital investment needed for replacement of the manufacturing plant. The current price of aluminum sheet is considered to be more in line with those replacement costs.

Dow has a continuous laboratory laminating line at its Midland Research Center that is capable of producing 3 ft. wide laminate. Operating speed and production capability of the line were not revealed other than that the system has sufficient capacity to produce laminate for current evaluation purposes and initial applications. The system has also provided Dow with the data and know-how needed to build a production facility when the demand for laminates would justify its construction. Dow is currently studying the effects of long term environmental exposure of the properties of its laminates. As part of this evaluation effort, Dow has fabricated metal-plastic laminate components with in-house tooling and has placed these components on company vehicles in order to obtain some in-use data. One of these components is a deck lid for a 1979 Ford Mustang which the principal investigator was able to examine. The metal-plastic laminate deck lid weighs 14.5 lbs., or 7.5 lbs. less than the original steel deck lid. The metal-plastic laminate deck lid did not appear different than the steel deck lid of another Mustang that was parked nearby. The metal-plastic laminate deck lid appeared more rigid than the original equipment. Because the original spring was not replaced, the metal-plastic laminate was not a sufficiently heavy counter-weight, and moved with disconcerting rapidity when the trunk lock was opened.

9.2.3 Hercules Inc.

Hercules Inc. has had an on-going research effort in metal-plastic laminates since 1973, with a significant level of activity for the past three to four years. The Hercules effort is keyed to the development of a polypropylene co-polymer which bonds to steel without the need for a separate adhesive. While most of the efforts have been directed towards steel faced laminates, in a joint development effort with the National Steel Co., the Hercules polypropylene co-polymer core has also been used to make aluminum or stainless steel laminates. The interest in stainless steel faced laminates was generated outside the automotive industry. There is an on-going in-house effort to establish the environmental stability characteristics of self-adhesive polypropylene core laminates. The results of these tests will be released later this year. Hercules has chosen the trade name of LITEPLATE for its laminates. Hercules is also working with three outside groups that have continuous or semi-continuous laminating facilities. Hercules believes that there is sufficient capacity currently available to produce about 10^7 ft^2/year (10^6m^2/yr).

There is also work being undertaken in the area of forming of automotive parts. Representative prototype parts are represented in Figure 9-1. Even though two appearance parts are shown in the photograph, Hercules believes that the initial use of laminates will be in miscellaneous non-safety critical parts that do not require a Class A finish. Likely applications should include load floors, covers, brackets, and similar hang on parts. Use in appearance body parts will be slow to develop because of poor compatibility with current manufacturing operations.

9.2.4 Monsanto Corporation

Monsanto Corporation has a visibly significant research and development effort devoted to nylon 6-6 core laminates. The principal efforts are directed towards aluminum-nylon laminates which have been given the trade name of "Analam." Even though nylon-steel laminates are being explored, Monsanto is focusing on aluminum faced laminates because these are considered to offer the greatest weight reduction potential, are more corrosion resistant, and could be fabricated today in widths of up to 50 in. (122 cm). Monsanto justifies the use of a nylon 6-6 core instead of a less expensive polyolefin core on the basis of improved laminate properties, in particular stability at paint bake oven temperature, stability at sub-zero conditions, and improved dent resistance. Furthermore, Monsanto believes that since it is completely vertically integrated in the manufacture of nylon 6-6, the cost of the nylon 6-6 in the core to a captive laminating facility will be less than the current price of extrusion grade nylon 6-6 molding powder. "Analam" laminates will be priced on a unit area basis, at a level intermediate to the prices of steel and aluminum sheet projected for the 1985-1990 period. Current research activities include improved methods of laminate manufacture, evaluation of steel faced laminates, environmental testing of laminates, evaluation of prototype automotive components, fastening and assembly methods, and recycling and reclamation of laminate scrap.

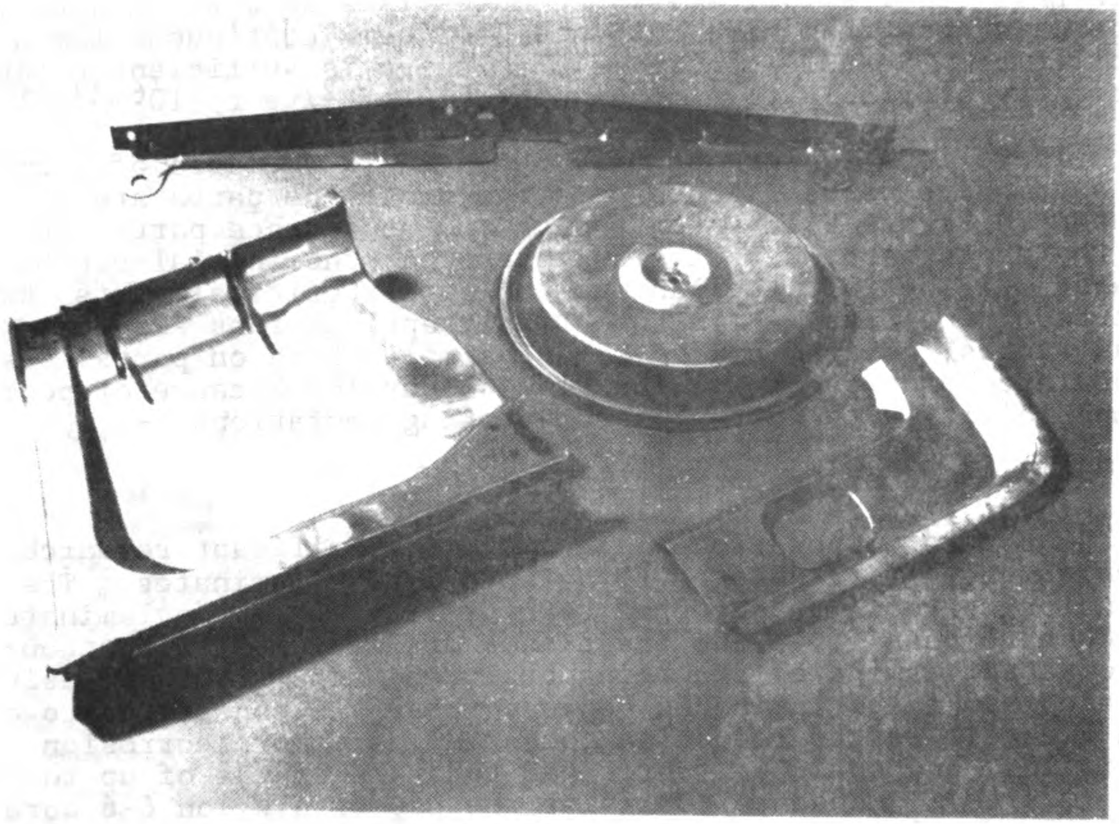

FIGURE 9-1 REPRESENTATIVE PROTOTYPE AUTOMOTIVE COMPONENTS FABRICATED BY HERCULES, INC. WITH STEEL-POLYPROPYLENE-STEEL LAMINATE

Clockwise from lower left: Inner cowl panel from a van, Front end support bracket for a G.M.C. X-car, Air cleaner cover, Roof extension bracket for a van.

9.2.5 Morton Chemical Company

Morton Chemical Company's interest in metal-plastic laminates is as a potential supplier of Morprime, a proprietary product of the company, as an adhesive for polypropylene core laminates. Morprime is a dispersion of polypropylene particles in a hydrocarbon solvent that shows good adhesion to most metals and to polypropylene. At the moment, Morprime is the only adhesive approved for use by the Federal Drug Administration for use to bond the interplies of flexible retort pouches (i.e., a retort pouch is a flexible food can). In terms of structural laminates, it has been found that Morprime does not adhere well to cold rolled steel, but adheres very well to electrolytic chrome coated steel. Morton is currently evaluating the stability of various metal plastic laminates in conjunction with the respective face sheet and core material suppliers.

9.2.6 Phillips Chemical Co.

Phillips Chemical Co. is starting an active evaluation program on metal-plastic laminates that is based on technology developed by the company over a decade ago. Based on this work, G. Harvey of Phillips was issued a U.S. Patent 3,542,605 (November 24, 1970) which covered the bonding of polyolefin to metal pre-treated with chromium trioxide. (Note: Stelco Inc. has similar patents). With this process, it is possible to bond either aluminum or steel to high density polyethylene without difficulty. Some problems have been encountered with the adhesion of polypropylene using this patented approach. At the time, laminate sheets up to 4 ft x 8 ft in size were fabricated on plywood presses. The work was abandoned for lack of commercial interest until it was resuscitated this year.

9.2.7 U.S. Steel Corp.

U.S. Steel Corp. is listed under polymer suppliers because the Novamont division of the company would be the likely supplier of polymers for metal-plastic laminates that would be supplied by U.S. Steel. This company's interest is discussed in more detail in Section 9.2 dealing with steel sheet suppliers.

9.2.8 Mitsui Petrochemicals Inc.

Mitsui Petrochemicals Inc. markets aluminum-polyethylene laminates under the "Planium" trademark. This product was introduced into commerce in Japan about five years ago. The principal application has been in bathroom and kitchenette modules for prefabricated housing. There has been little interest in this material on the part of U.S. and foreign automotive component manufacturers. Mitsui has a continuous laminating line which produces a product 1.25 meters wide at a production rate of about 500 to 1000 m^2/hr. It would be possible to produce a 1.4 meter wide product with this facility. Mitsui is trying to introduce

"Planium" into the U.S. architectural market where it would be in competition with Alucobond. (Consolidated Aluminum Corp.).

9.2.9 Other Foreign Polymer Suppliers

In addition to the above, the following two foreign chemical manufacturers appear to have interest in the technology. These firms were not directly contacted during the course of the study.

Based on the extensive numbers of patents issued to BASF A.G., a large West German chemical manufacturer, this company would be expected to have significant interests in the metal technology. Solvay & Cie (Belgium) has recently introduced a line of metal-plastic laminates under the "Strapan" trademark that are 1mm to 3mm thick. Various face sheets are used over an unspecified core material.

9.3 STEEL PRODUCERS

Among the steel producers, there is cautious interest in metal-plastic laminates on the part of manufacturers of tin mill producers, i.e., suppliers of sheet steel in the thin gauges that would be required for laminates that would replace automotive sheet steel. The North American steel producers that have been identified as having an active interest in metal-plastic laminates include Bethlehem Steel Corporation, National Steel Corporation, Stelco Inc., and U.S. Steel Corporation. These companies are pursuing the development of steel faced metal-plastic laminates principally as a defensive measure against the potential in-roads of other light weight materials in automotive structures. There is ambivalence in this activity in that these laminates, if brought to successful commercial development, would be competing against heavier gauge sheet steel, which is a bread and butter item for these companies, and would reduce the overall tonnage demand for steel by the automotive industry. However, by offering steel faced laminates, the steel industry would provide the automobile industry a lightweight material option (other than aluminum or plastics) that contains steel. While less steel would be sold if steel faced laminates were to replace the all steel sheets now used, this would be a preferred situation to the total displacement of steel from the automotive market by aluminum or plastics. The polymer producers viewed laminates as potential proprietary product lines that could support higher profit margins than the individual components taken separately. This attitude was not as prevalent among the steel manufacturers, even though there are strong advocates for laminates within the individual steel companies because these specialty materials represent an opportunity for a manufacturer to sell a product other than a low margin commodity material.

9.3.1 Bethlehem Steel Corporation

Bethlehem Steel Corporation has had a modest research and development activity in metal-plastic laminates for the past two years. The activity has centered on the development of adhesively bonded ECC steel-talc filled polypropylene laminates. Test programs include evaluation of the environmental resistance of the laminates, limited manufacturing development activity directed towards batch lamination, and joining and fastening studies. Many unexposed parts have been identified as the likely components to be manufactured from laminates.

9.3.2 National Steel Corporation

National Steel Corporation has had an R&D group investigating metal-plastic laminates for the past few years. In conjunction with Hercules Corp., National Steel has a program directed towards product development and characterization of steel-polypropylene laminates, and application and market development activities. Various laminate manufacturing methods are being investigated, including platen press processing, semi-continuous and continuous methods. At present, only laminates made on platen presses are available in sizes ranging from 24 in x 48 in to 36 in x 96 in. National Steel is also carrying out experiments on the rolling of wide thin gauge steel sheets on production cold roll mills. These experiments involve the feasibility of producing sheets as thin as 0.010 in. in widths of up to 48 in.

9.3.3 Stelco Inc.

The Steel Company of Canada, Inc. (Stelco) is currently assessing the potential of metal-plastic laminates. It has developed proprietary laminating technology involving the use of chromium oxide treatment of the metal sheets to promote the adhesion of a olefin copolymer core. This technology is covered in U.S. Patents 3,679,513 (July 25, 1982) and 3,826,628 (July 30, 1974) issued to R. L. Addinall et al. This technology is related to technology developed by Phillips Chemical Co. Stelco's interest in laminates derives, in part, from confidence in its ability to make wider thin gauge than its North American competitors (the upper width values in Table 4-10 are based on discussion with Stelco representatives), and in part because of its fifty percent ownership of Baycoat Ltd., the largest coil coating firm in Canada.

9.3.4 U.S. Steel Corporation

U.S. Steel Corporation is currently studying the market potential of metal-plastic laminates. There is strong interest in these materials on the part of Tin Mills Product group and the U.S.S. Novamont Inc. subsidiary which is a major producer of polypropylene. Metal-plastic laminates would represent new markets for the products of both these groups. In support of its market evaluation activities, U.S. Steel has contracted Prefinish Metals Inc., a coil coater in Elk Grove Village, IL, to produce a full coil of steel-polypropylene laminate on a developmental basis. U.S. Steel would be providing the raw materials.

which Pre-Finish Metals would combine in semi-continuous fashion on its coil coating line. If this imminent trial run were successful, U.S Steel would have available sufficient laminate made in a realistic production manner that would be used for evaluation tests by potential users in the automotive industry.

9.4 ALUMINUM SHEET PRODUCERS

There is currently no apparent interest on the part of the aluminum industry in metal-plastic laminates for automotive uses. For lack of any indication of such activity in the technical press, the secretary of the Automotive and Truck Committee of the Aluminum Association was contacted to ascertain whether members of the committee were aware of development efforts within their companies related to automotive uses of aluminum-plastic laminates. A polling of the membership of the committee indicated no such activities (9-1).

As indicated in Chapter 2, Consolidated Aluminum Corporation, St. Louis, MO, is manufacturing and selling thick aluminum-polyethylene laminates primarily for architectural and interior design purposes. This company has the only continuous commercial laminating facility currently in operation in the U.S. today. This facility can produce ten to twenty million square feet per year of Alucobond. There is no active interest on the part of Consolidated Aluminum to pursue the automotive market, except for specialty situation with its existing products, nor to develop thinner laminates that would be required for most automotive applications.

9.5 COIL COATERS

Coil coating is the pre-finishing of coils of sheet metal. It involves specialized facilities in which a coil is taken through a series of steps that are necessary to apply a long lasting corrosion resistant or decorative coating to the sheet. In a typical coil coating operation. a metal coil is unwound, and the sheet metal is straightened. cleaned, painted, oven cured and re-coiled in continuous series fashion. The same equipment is also used to bond a plastic film to the metal sheet. While some metal sheet producers also operate captive coil coating facilities, there are many independent companies that perform coil coating on a toll basis (9-2).

The coil coaters have a strong technology and experience base to draw on, as well as facilities for the manufacture of metal-plastic laminates, at least on a semi-continuous basis. The independent coil coaters. however, do not have the resources to perform long-term research and development without external support that would have to come from the suppliers of the component materials used in laminates, or from potential users of laminates. Arvin Industries. Inc. and Pre Finish Metals, Inc., were two coil coaters identified as having an active interest in metal-plastic laminates. It is quite likely that other firms with similar capabilities share these interests.

9.5.1 Arvin Industries, Inc.

Arvin Industries, Inc. has two divisions that would have capabilities to manufacture metal plastic laminates. These are the Arvinyl Division in Columbus, IN, and the Roll Coater, Inc. division in Greenfield, IN. Arvinyl produces decorative one side vinyl to metal laminates, and fabricates parts, primarily from these coated materials, for a variety of end uses. Arvinyl has also initiated production of sound damping steel-visco elastic plastic-steel sandwich laminates. Programs are underway with major engine manufacturers to develop oil pans and valve covers from these damped metal laminates. Arvinyl was contacted about three years ago by two of the raw material suppliers who were looking for firms that could manufacture the type of metal-plastic laminates of interest to this study. Arvinyl has performed some model shop experiments with platen press lamination, but has not yet carried out any continuous lamination work. Arvinyl, however, has laboratory facilities where small scale continuous lamination tests could be performed.

Roll Coater Inc. is the largest coil coater in the nation. It has four coating lines including a new 72 in. wide line at Kingsbury, TN, which with some modification, could be used to make laminates on a semi-continuous basis.

9.5.2 Pre Finish Metals, Inc.

Pre Finish Metals of Elk Grove Village, IL is an independent coil coater with three coil coating lines. The company has been interested in metal laminates for about fifteen years, but for lack of prior commercial interest in these products, an active development program was initiated only a few years ago. It has been carrying out manufacturing development work on metal-plastic laminates, for its own account and in conjunction with a number of material suppliers, principally steel companies. Pre Finish Metals, Inc., as previously mentioned in Section 7.2, has successfully laminated 4000 lb. steel-polypropylene-steel laminate on one of its coil coating lines at a speed of about 100 ft/min. per pass. It is presently gearing up to handle larger size coils.

Pre Finish Metals, Inc. is reviewing its business position with regards to metal-plastics laminates. The options being considered include manufacturing laminates for its own account, manufacturing laminates on a toll basis for another party, or providing engineering and consulting services to other firms who would be interested in producing metal-plastic laminates.

9.6 AUTOMOTIVE COMPONENT AND VEHICLE MANUFACTURERS

Based on discussions with General Motors Corporation, Ford Motor Company, and The Budd Company, it appears that there is research interest within different groups at each of the major manufacturers. However, metal-plastic laminates are new materials for the automotive industry and significant further investigation is required before a metal-plastic laminate part is to be qualified for production use. At present, no metal-plastic laminate component is scheduled for use on any production vehicle.

9.6.1 General Motors Corporation

There are a number of separate development efforts within General Motors Corporation where metal-plastic laminates are being considered as candidate materials for specific components. While the design criteria are complex, stiffness critical components are considered to be the logical applications of metal-plastic laminates. Because of corrosion and paint bake limitations, the parts being considered are small, unexposed components that do not require painting and are out of corrosion areas. When queried about which specific components were being investigated, the General Motors representative suggested that sufficient examples of G.M.'s activities in metal-plastic laminates were already mentioned in the technical press. Specific programs attributed to GMC include the evaluation of steel-polypropylene laminates for fender liners and engine rocker covers by the Pontiac Division, and seat frames by the Fisher Body Division (9-3). There is concern that the developmental prices of laminates may be so high (i.e., close to the price of aluminum sheet) as to discourage interest in these materials, since at equal price, aluminum, because of its familiarity, is a more attractive material.

9.6.2 FORD MOTOR COMPANY

Ford Motor Company has assembled a task force to assess potential automotive applications of metal-plastic laminates. The task force report is to be issued this Fall. It has obtained evaluation samples of various metal-plastic laminates being offered by different developers, and is also examining prototype components made from these laminates. A specific example of a stamped part is the third door upper frame for the Erika. While originally very enthusiastic about metal-plastic laminate technology, a number of uncertainties have arisen which are damping serious interest in the potential use of metal-plastic laminates in production parts. These uncertainties include:

- The availability of metal-plastic laminates
- Current and projected costs of metal-plastic laminates
- Variability in material properties

- Weight savings lower than anticipated

- Performance of metal-plastic laminates

With regards to the last point. Ford in general mentioned the design and fabrication constraints outlined in Chapters 4 and 5. Weight savings obtained were observed to be closer to 30 percent than the 40 to 50 percent value that was anticipated. The lower weight reduction may be due in part to the current availability of less than optimal materials for the applications intended.

9.6.3 The Budd Company

The Budd Company has been examining the potential transportation applications of metal-plastic laminates at its Fort Washington Technical Center for its own account, and for other firms on a contractual basis. These efforts date back fifteen years. While some forming and testing work is being performed for various clients, metal-plastic laminates are not considered sufficiently attractive to warrant expenditure of internal company funds on applications of these materials. As part of prior test efforts, some impact tests were performed on laminates to establish their behavior in crash situations. These preliminary results indicate no weight or cost saving would occur from the substitution of steel metal-plastic laminates in crash parts.

9.7 SUMMARY

While there is a general belief that metal plastic laminates will definitely find their applications in the automotive industry, significant further investigation is required to qualify them for any production use. The recent spate of publicity given metal-plastic laminates in the technical and business press may prove to be counter-productive in terms of the long-term development of the technology, in that expectations and interest were inflated beyond what could be justified in terms of current capabilities and levels of development.

Metal-plastic laminates are new materials to the automotive industry, and further familiarization with the properties and limitations of the materials on its part is required. Optimal materials for automotive applications, in terms of properties, manufacturing methods, and costs are still to be perfected.

The ability to make metal-plastic laminates on a semi-continuous basis on coil coating lines on a toll basis will be a key factor in the development of the technology in that improved laminate could be made available at lower cost and in sufficient quantities to satisfy developmental and initial qualified production, without requiring the need to risk major capital investments in high volume laminate production facilities before the market for these laminates is well defined.

CHAPTER 9 REFERENCES

9-1 Mr. G. A. Alison, The Aluminum Association, Inc., Personal Communication, June 5, 1980.

9-2 National Coil Coaters Association, 1980, Product Capability Directory, Philadelphia, PA, 1980.

9-3 A. Wrigley, "Laminates Can Make It Big -- If The Price Is Right," Ward's Auto World, p. 22, May 1980.

10.0 PROJECTED FUTURE STATUS OF METAL-PLASTIC LAMINATE TECHNOLOGY

The general consensus is that metal-plastic laminates will find their niche in the automotive industry. The questions that are unresolved are where, when, and how much.

The nearer term use of metal-plastic laminates will be in low risk applications where current generation laminates can be used effectively within the constraints of existing automotive manufacturing practice. This curtails the use of laminates to small, non-visible parts that do not have a safety critical function and where stiffness is the design criterion. Because of cost considerations, laminates will be candidates primarily for parts which have a low offal rate. Furthermore, parts now made of heavy gauge steel (1.25 mm or 0.050 in. and above), to the extent that they are not strength critical parts, would be more attractive than parts made of thinner gauge steel. In general, since parts on light duty vehicles tend to be thicker than the equivalent parts on a passenger automobile, metal-plastic laminates may well be used first on pick up trucks and vans rather than passenger automobiles. Furthermore, since downsizing is not a viable option for a light duty vehicle designed on a functional basis, weight reduction by material substitution will be relatively more important as a means of achieving improved fuel economy than it will be for passenger automobiles, which can be made smaller and still retain most of their functional characteristics. Representative parts include brackets, access hole cover plates, shrouds and similar items. Most of these parts will be made of steel-polypropylene laminates, and will be sufficiently small so that current width constraints on steel sheet will not matter. Total usage of laminates in these applications could be as much as 2.5 m^2 vehicle (29 ft^2/vehicle).

Further use of metal-plastic laminates will be based on increased familiarity with, and confidence in, metal-plastic laminates by automotive designers, and with the availability and use of metal-plastic laminates of lower cost and/or improved performance characteristics. Larger parts may be considered, such as interior panels and load floors, which may require wider laminates (48 in. (112 cm) or more) that are able to withstand passage through the electrocoat primer ovens. It will be necessary to consider nylon 6-6 or thermoplastic polyester core laminates for these applications, since it is believed that the operating temperatures of the electrocoat paint oven will still be too high (greater than 300°F (150°C)) to allow polyolefin core laminates to be used. These applications could present an additional 10 m^2/vehicle (108 ft^2/vehicle).

Extensive application of metal-plastic laminates which would include their use in exterior appearance parts will only occur with significant changes in automotive manufacturing practice, and thus may never come to pass. The issues of in-plant repair of appearance parts, adhesive bonding, and development of methods of reinforcing attachment points are all problems for which technical solutions exist, and thus could be found, if there were sufficient interest to do so.

A projected upper bound estimate of the use of metal plastic laminates by the U.S. automobile industry is given in Table 10-1. The reasoning behind this projected introduction is outlined in the more detailed schedule presented in Table 10-2. Initial production use of a small number of low risk parts is unlikely to occur before 1986. If successful, use of laminates in these parts would grow rapidly and could saturate by 1988. This success would justify further use of laminates in similar low risk parts in the 1987 to 1990 period. More extensive use of laminates in larger, higher risk parts on a limited number of production vehicles would follow but would not occur before 1989 to 1990.

Figure 10-1 summarizes the range of the projected demand for metal-plastic laminates based on the automotive use outlined in Table 10-1. This figure assumes a 30% average scrappage factor which is characteristic of the automotive industry. This scrappage level may be high since laminates would tend to be used in parts which have low scrap rates. By 1990, low risk applications would create a maximum demand for about 36 million square meters per year of laminate. This corresponds approximately to the output of two large continuous laminating plants assumed to have a 3 shift capacity of 17 million square meters/year each as discussed in Chapter 7. The lower bound estimate would correspond to about 7 million square meters/year which would be sufficient to keep these two facilities operating on a one shift basis. Unless some higher risk applications of metal-plastic laminates develop, there will be sufficient demand for two suppliers only. If the higher risk applicatons come to pass, this could create a demand for an additional 57 million square meters/year which would correspond approximately to the output of three large laminating plants on a three shift a day basis. These additional facilities would be likely to produce a different material than the first two. Based on a nominal selling price of $5/square meter, low risk applications represent a future business volume of $45 million/year to $175 million/year. The higher risk applications would represent an additional volume of $300 million in 1991, and potentially $700 million/year if 10 m^2/vehicles were used for the total production, assumed to be 10 million vehicles/year.

These figures indicate that many of the current developers of metal-plastic laminates will drop out since ultimately there will only be sufficient business to support two laminate suppliers if the volume of business is limited to low risk automotive applications. If higher risk automotive applications were to develop, this additional volume could support three additional laminate suppliers. These projections do not include any other potential non-automatic applications of metal-plastic laminates that could develop.

It is also to be noted that batch plants would not be able

TABLE 10-1

UPPER BOUND ESTIMATE OF PROJECTED AUTOMOTIVE USE OF METAL-PLASTIC LAMINATES

LAMINATE USE PER VEHICLE			
M^2/VEHICLE	0.1 - 0.5	0.5 - 2.5	2.5 - 12.5
PERCENT SHEET METAL USE	0.3 - 1.6	1.6 - 8.0	8.0 - 40.0
YEAR		**NUMBER OF VEHICLES**	
1984 - 1985	2,000*	-	-
1986	400,000	4,000*	-
1987	4,000,000	400,000	-
1988	6,000,000	4,000,000	4,000
1989	-	10,000,000	400,000
1990	-	10,000,000	400,000
1991	-	6,000,000	4,000,000

* TEST VEHICLES

TABLE 10-2

PROJECTED TIME-LINE QUALIFICATION SEQUENCE FOR METAL-PLASTIC LAMINATES

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
IDENTIFY LOW RISK COMPONENTS	———	———										
DEVELOP MANUFACTURING PLAN FOR CANDIDATE COMPONENTS	———	———	———									
DEMONSTRATE SEMI-CONTINUOUS OR CONTINUOUS LAMINATE MANUFACTURING	———	———	———									
ESTABLISH PRODUCT SPECIFICATIONS FOR ABOVE LAMINATE			———	———								
PERFORM COMPONENT FIELD TRIALS IN LIMITED NUMBER OF VEHICLES			———	———								
SMALL FLEET (1,000 VEHICLES OR LESS) OF CANDIDATE COMPONENTS)					———	———						
ESTABLISH CANDIDATE PARTS FOR LARGE FLEET TEST (200,000 VEHICLES EACH WITH TWO MANUFACTURERS)						———						
LIMITED FIELD TESTS OF SECOND GROUP OF LAMINATE COMPONENTS						- - -	- - -					
INITIATE LARGE FLEET TEST - PRODUCTION PLAN FOR FOLLOWING MODEL YEAR							———					
INITIAL QUALIFIED PRODUCTION USE OF METAL-PLASTIC LAMINATE COMPONENTS								X				
LARGE FIELD TESTS OF SECOND GROUP OF LAMINATE COMPONENTS								- - -				
EXTENSIVE PRODUCTION USE OF METAL-PLASTIC LAMINATES IN LOW RISK COMPONENTS									X			
LIMITED FLEET TESTING OF HIGHER RISK COMPONENTS									═══			
SATURATED USE OF METAL-PLASTIC LAMINATES IN LOW RISK COMPONENTS										X		
LARGE FLEET TESTING OF HIGHER RISK APPLICATIONS OF LAMINATES (CONTINGENT RISK)										═══	═══	
INITIAL PRODUCTION USE OF LAMINATES IN HIGHER RISK COMPONENTS												X

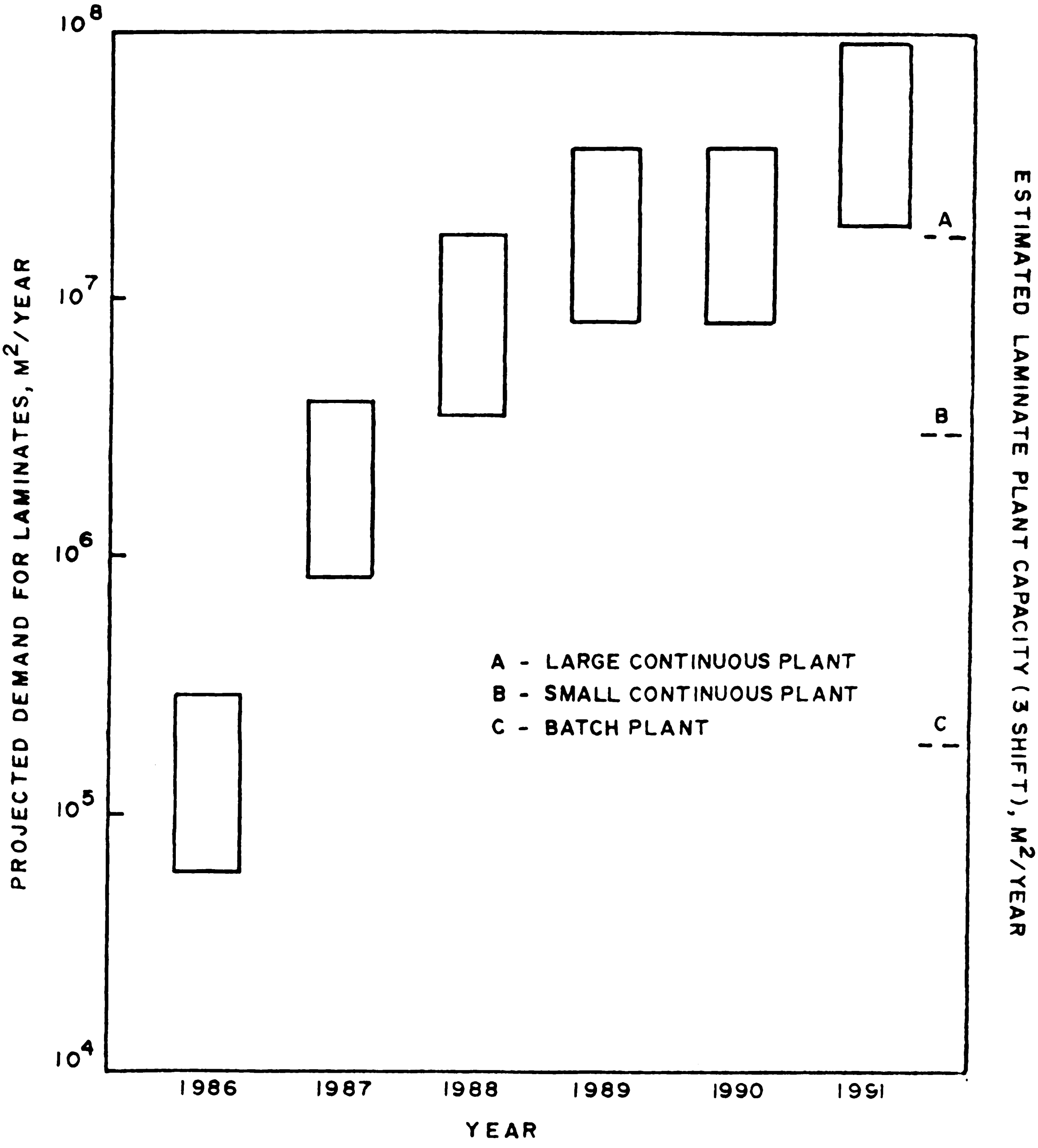

FIGURE 10-1. PROJECTED RANGE OF UPPER BOUND ESTIMATE OF AUTOMOTIVE DEMAND FOR METAL - PLASTIC LAMINATES FROM 1986 TO 1991

to produce sufficient laminate beyond the entry year of 1986, and that small continuous plants could supply the projected use through 1988, but would have to compete with larger facilities that produce laminates at lower cost in 1989 and beyond. Because of this risk of rapid obsolesence of smaller facilities, and because of the ability to laminate on existing coil coating lines on a toll basis at a cost comparable to that of a small continuous laminating facility, it is unlikely that these smaller facilities (i.e., 2 million sq. meters/yr) will be built, except possibly for the manufacture of special grades of laminates where, for reasons of thickness or of a safeguarding secret technological know-how, it would not be desirable to laminate at a coil coating facility. For this projected use to occur, a significant long-term investment will be required on the part of the interested companies, principally the various material suppliers. The automotive and component manufacturers will be interested in using laminates once it has been demonstrated that they are a viable lightweight material in terms of performance, cost and availability. For each candidate application of metal-plastic laminates, the supplier will have to provide the potential user with the information and means necessary required to manufacture the specific candidate component out of the particular type of metal-plastic laminate the supplier wishes to sell. A total system approach is required in which each of the following items will have to be resolved:

- Part design and configuration
- Weight savings and other performance benefits relative to other materials
- Reliability in operation
- Manufacturing plan which identifies equipment and tooling needs, fabrication process details, labor requirements, etc.
- Assurance as to the availability, quality and cost of the metal-plastic laminate that would be used in the application
- Cost advantages (or penalties) of making the specific component out of metal-plastic laminate rather than from a competing product.

Some of the research and development actions that such an effort would require are outlined in Table 10-3. All these action items will require time and money. Items Number 4 (Development of a data base), Number 6 (Crashworthiness evaluation) and Number 10 (Reclamation and Recycling) would be appropriate areas of research that could be supported by the Federal government.

Based on the laminate use projection presented in Table 10-1, metal-plastic laminates will have little impact on the fuel

TABLE 10-3

REPRESENTATIVE RESEARCH AND DEVELOPMENT ACTIVITIES THAT WILL BE REQUIRED TO SUPPORT THE USE OF METAL-PLASTIC LAMINATES BY THE AUTOMOTIVE INDUSTRY

1. IDENTIFICATION AND SYSTEM ANALYSIS OF CANDIDATE APPLICATIONS
2. MANUFACTURING DEVELOPMENT OF SEMI-CONTINUOUS AND CONTINUOUS PROCESS
3. DEVELOPMENT OF NEW LAMINATES WITH IMPROVED PERFORMANCE AND LOWER COST
4. DEVELOPMENT OF A PROPERTIES DATA BASE FOR METAL-PLASTIC LAMINATES OF INTEREST TO THE AUTOMOTIVE INDUSTRY
5. EXAMINE IMPROVED METHODS OF FORMING THIN GAUGE SHEETS IN GENERAL, AND LAMINATES IN PARTICULAR
6. DETERMINE CRASHWORTHINESS OF METAL-PLASTIC LAMINATE COMPONENTS
7. DEVELOP IMPROVED METHODS OF JOINING THIN MATERIALS BY ADHESIVE BONDING APPLICABLE TO AUTOMOTIVE MANUFACTURING
8. DEVELOP IMPROVED METHODS OF IN-PLANT REPAIR COMPATIBLE WITH METAL-PLASTIC LAMINATES
9. MANUFACTURING DEVELOPMENT OF WIDE THIN GAUGE METAL SHEETS
10. EXAMINE CONSTRAINTS ON RECLAMATION AND RECYCLING OF METAL-PLASTIC LAMINATES

economy of the fleet of production automobiles at least through 1990. Based on the weight of sheet metal in a 1978 Omni sedan, as reported in Table 8-2, and an assumed weight savings due to laminate substitution of 40 percent of the weight of sheet metal replaced, replacement of 8 percent of the on-board sheet metal by metal-plastic laminate, the most optimistic projection through 1990, would represent an average weight savings per vehicle of 23 lbs (10 kg), or approximately one percent of the current curb weight of the vehicle. The fuel economy improvement that would be obtained as a result of an upper bound projection of one percent weight savings is not discernable within the uncertainty with which such a projection can be made.

Beyond 1990, if laminates were to ultimately replace 40 percent of the sheet metal on-board an automobile, the projected direct weight savings could attain 190 lbs. (86 kg), or 9 percent of the total vehicle weight. Since a significant fraction of the laminate would be used in upper body components, a significant additional weight savings would be expected. Under these circumstances, laminates would have a noticeable impact on the fuel economy of an automobile. The same reasoning would also apply to light duty vehicles.

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APPENDIX B

MECHANICAL PROPERTIES OF SANDWICH LAMINATES

B-1 INTRODUCTION

Mechanical properties of a sandwich laminate differ from those associated with homogeneous sheet material. To a first order approximation, sandwich design will depend on the relative thickness and properties of the face skins and core. As previously noted, a sandwich panel is analogous to an I beam with facings and core corresponding to the flanges and web. The facings carry axial compressive and tensile forces. The core sustains shear stresses, and because of its essentially continuous support of the skins, it increases their resistance to wrinkling or buckling under axial compressive load. When thick facings are used, these may be subject to significant shear stresses. The adhesive is subject to shear and to transverse tensile stresses caused by the tendency of facings to buckle under axial compression.

B-2 FLEXURAL STIFFNESS OF A SANDWICH LAMINATE

The stiffness S of a rectangular beam of thickness t, width b and modulus of elasticity E is given by the formula

$$S = \frac{Ebt^3}{12} \tag{B-1}$$

If a sandwich is constructed with the same over-all thickness, but a core of different material of thickness, t_c, the stiffness of the sandwich is expressed as

$$S = \frac{(E_f b(t^3 - t_c{}^3) + E_c b t_c 3)}{12} \tag{B-2}$$

where E_f is the modulus of elasticity of the facings and E_c is the modulus of elasticity of the core. In the sandwich structures of interst where $E_f >> E_c$, equation B-2 can be written as:

$$D = \frac{E_f b(t^3 - t_c{}^3)}{12} \tag{B-3}$$

In terms of the core volume ratio, α, since $\alpha = t_c/t$, this last equation can also be expressed as:

$$D = \frac{E_f b t^3}{12} (1 - \alpha^3) \qquad \text{(B-4)}$$

The above equation for flexural stiffness does not fully define the deflection of a sandwich beam under flexural load. In a sandwich, deflection due to shearing deformation may be important because of the low shear modulus of the core. The general expression for the deflection of a sandwich beam is

$$y = \frac{k_b P a^3}{S} + \frac{k_s P_a}{\bar{N}} \qquad \text{(B-5)}$$

where y is the deflection, P the total load, a the span. S the flexural stiffness given by equation B-4 above, and $\bar{N}$ is defined by the following equation:

$$\bar{N} = \frac{b G_c t}{2} (1 + \alpha) \qquad \text{(B-6)}$$

in which G_c is the shear modulus of the core. k_B and k_S are constants that depend on beam loading. Note that for a long span, the first term of equation B-5 will be of more consequence than the second term. Shearing deflections become of significance only for very short spans. The critical distance at which shear induced deflection is equal to flexural deflection is of the order of 1 cm to 2 cm for steel-polypropylene-stell laminates with a core volume ratio of 0.6 and an overall thickness of less than 2.5 mm. For aluminum faced nylon laminates of similar thickness, but with a core volume ratio of 0.8, this critical distance is of the order of 4 cm to 8 cm.

B-3 IN-PLANE STIFFNESS OF A SANDWICH LAMINATE BEAM

The in-plane stiffness of a sandwich laminate beam is given by the following equation:

$$E_{s1} = \frac{2E_f t_f b + E_c t_c b}{t\ b} \qquad \text{(B-7)}$$

If $E_f >> E_c$, and the second term is neglected, Equation B-7 can be written as:

$$E_{s1} = 2E_f\ (1-\alpha) \qquad \text{(B-8)}$$

The in-plane stiffness is proportional to the fractional volume content of the face sheets.

B-4 FLEXURAL STRENGTH OF A SANDWICH BEAM

The strength of a sandwich beam under bending and shear load is determined by the ability of the facings to resist compression or tension, and that of the core to resist shear. The stress produced in the facings by bending moment applied to the sandwich are given by the formula

$$F = \frac{2M}{t_f(t + t_c)b} \qquad \text{(B-9)}$$

or, in terms of α,

$$F = \frac{4M}{bt^2 \; (1 - \alpha^2)} \qquad \text{(B-10)}$$

In the above, F is the mean compressive or tensile stress in the facings, M is the bending moment, t_f is the thickness of a facing, and the other terms are as defined previously.

The shear stress in the core is given by, if V is the applied shear force,

$$s_c = \frac{2V}{(t + t_c)\; b} \qquad \text{(B-11)}$$

or in terms of α,

$$s_c + \frac{2V}{tb\; (1 + \alpha)} \qquad \text{(B-12)}$$

B-5 IN-PLANE STRENGTH OF A SANDWICH LAMINATE

When a sandwich laminate is subject to an in-plane tensile load, if the core is significantly weaker than the face skins, the total load is carried by the face skins. The in-plane strength of the laminate is proportional to the strength of the face skins and their volume fraction, i.e.

$$\sigma_{s1} = \;{}_{f}\,(1-\alpha) \qquad \text{(B-13)}$$

where σ_{s1} is the in-plane tensile strength of the laminate and σ_f is the tensile strength of the face skins.

Sandwich laminate, however, is more effective in terms of supporting an in-plane compressive load where the design is a function of either the buckling resistance of a sandwich column or of the ability of the sandwich to resist direct compression in the face skins, which ever is the lesser.

Compressive stresses in the face skins are given by:

$$\sigma_C = \frac{P}{2t_f b} \qquad \text{(B-14)}$$

If the panel is simply supported at its ends, the column buckling load is given by

$$P = \frac{\sigma_C^2 S}{L^2(1 + \sigma_C^2 s/L^2 N)} \qquad \text{(B-15)}$$

where P is the total load, σ_C are the compressive stresses in the face skins, t_f is the face skin thickness, b the width, D is defined by Equation B-4, and N is defined by Equation B-6. The second term in the denominator of equation B-15 accounts for possible shear deformation in the core.

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The above discussion was adapted from Reference B-1. The other references provide more detailed discussions of the mechanical properties of sandwich laminates.

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APPENDIX C

PATENTS

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APPENDIX D

LAMINATE MANUFACTURING AND COST ANALYSIS

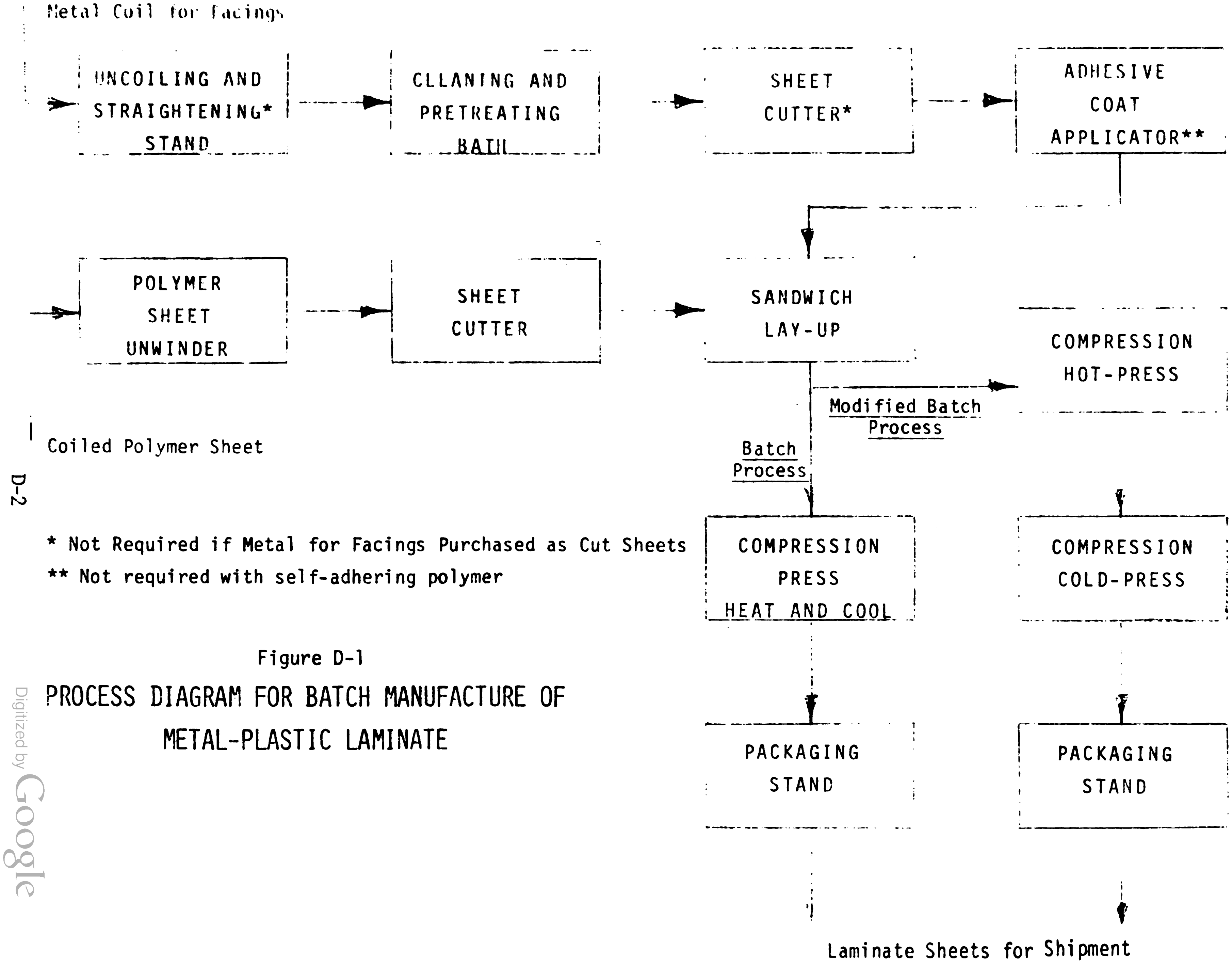
D-1 BATCH LAMINATION

Batch Lamination is a simple process in which a sandwich consisting of a sheet of thermoplastic polymer layered between two metal sheets, is placed between the flat platens of a compression press. The platens, which are designed to be either heated (or cooled) are closed and first heated so that the sandwich is heated under pressure to a temperature high enough to melt the polymer or adhesive. This results in the melting by the polymer of the internal surfaces of the metal skins. The platens are then cooled, which in turn cools the sandwich to a temperature below the melting point of the polymer or adhesive, resulting in the formation of a laminate. The laminate is removed and another sandwich is placed in the press to start the cycle again.

A process diagram for the batch manufacture of metal-plastic laminate is outlined in Figure D-1. In addition to a press, equipment is required for receiving, preparing and handling the sheet metal used for the skins and the polymer sheet needed for the core, as well as for packaging and handling the laminated product. The modified batch process outlined in Figure D-1 will be discussed subsequently.

The production capacity in this process is established by the size of the sheet being laminated and the cycle time. A common press size has platens slightly larger than 4 ft x 8 ft (122 cm x 244 cm). The time required (as well as the energy requirements) are established by the time required to heat and cool the platens which may be 5 cm or more thick. The thermal resistance of the 0.2 mm thick face sheets of a 1 mm laminate is negligible in comparison to the thermal resistance of the much thicker platens. Heating the platens from room temperature to 200°C (392°F) may require approximately 15 min. to 30 min. with a slightly shorter period of time required to cool from operating to room temperature. This is significantly longer than the time that would be required to raise the temperature of the metal-skin-polymer core interface from room temperature to the polymer melt temperature when a laminate is placed between pre-heated platens. Assuming that a platen surface acts as constant heat source operating at 200°C, the skin-core interface of a laminate with 0.2 thick skins, originally at 30°C, would attain 150°C in about 0.015 sec., assuming heat transfer as being due to conduction in one direction (D-1).

In order to increase machine output, a number of developers of metal-plastic laminates have been experimenting with an approach wherein a "book of laminate leaves," I.e. a stack of



* Not Required if Metal for Facings Purchased as Cut Sheets

** Not required with self-adhering polymer

Figure D-1

PROCESS DIAGRAM FOR BATCH MANUFACTURE OF METAL-PLASTIC LAMINATE individual sandwich assemblies, is placed in the interplaten space of a press, which is then closed and heated. The rational behind this approach is that capacity can be multiplied by the number of leaves in the book without changing press residence time. This approach to the problem invited difficulties in that it insures that the various sheets of laminates produced will have a different time-temperature history during fabrication making it difficult to maintain product uniformity and consistency. Control of the thickness of the laminate becomes very difficult. With one sandwich layer between the platens the thickness of the laminate is established by controlling the gap thickness between the platens which can be accurately controlled. With a stack of sandwiches in which the cores do not soften and melt simultaneously, it will be very difficult to maintain accurate control of the thickness of each of the various leaves of the book.

Finally, the thermal resistance of a stack of laminate sandwiches, even one that is only three high, is significantly higher than that of a single sandwich layer. Since it is not necessary to melt all of the polymer core, but only the polymer at the skin-core interface, to achieve subsequent bonding of metal skin to the core, when only one sandwich layer is present, the thermal resistance is only that of the metal skins. When more than one sandwich layer is present, heat then has to flow through one or more polymer cores to reach the skin-core interface of the sandwich in the middle of the stack. This will take much longer than the time necessary to heat one sandwich because the polymer core is a very good thermal insulator in comparison to the metal skin. The coefficient of thermal conductivity of the polymers of interest if of the order of 3 8×10^{-4} cal-cm/sec-cm^2-°C as compared to 0.14 cal-cm/sec-cm^2-°C for steel, and 0.50 cal cm/sec-cm^2-°C for aluminum. There is about a two to three order of magnitude difference in the thermal conductivity of the face skins and the core. When one laminate sheet is present, heat transfer into the laminate from the platen is controlled by the resistance of the face skin. With a stack of laminate sheets, heat transfer is controlled by the series resistance of the cores. Since the required residence time increases as the square of the number of leaves in the stack, the thermal resistance of the laminate can rapidly become comparable to that of the platens which would no longer be controlling.

One way of avoiding this problem is to use a multi-opening platen press similar to those being used in the plywood industry (D-2). In this case, a number of laminate sheets can be prepared simultaneously, but in a manner that allows each sheet to come into direct contact with a platen. The operating costs developed for the batch manufacture of metal-plastic laminates are presented in Table D-1 for various assumed hours of annual operation. The key assumption is that the output is based on a laminate sheet size of 1 m x 3 m, the lamination of 10 sheets at a time on an 11 platen press, and a press cycle time of 1 hour. It is assumed that 3 laborers are required to convert the cleaned prepared metal into a laminate, with two additional operators needed for metal cleaning and preparation. The capacity of the

TABLE D-1

OPERATING COST SUMMARY - BATCH MANUFACTURE OF METAL-PLASTIC LAMINATE ON MULTI-PLATEN PRESS

Shifts per day	1	2	3
Operating Hours per Year	2,000	4,000	6,000
Nominal Laminate Output, 10^3 square meters/yr	60	120	180
	Annual Costs, 10^3 \$ / year		
Direct Costs			
Operating Labor: 3 men/shift @ \$40K/m-yr + 2 men for 1 shift	200	320	440
Utilities	30	60	90
Miscl. Supplies	10	20	30
Sub-total	240	400	560
Capital Related Costs (Capital Investment in Physical Plant : \$0.85 Million)			
Depreciation			
Equipment @ 20% per annum	150	150	150
Buildings @ 5% per annum	5	5	5
Maintenance, Insurance, Taxes @ 10% of Plant Investment per annum	85	85	85
Interest on Capital Invested in Physical Plant @ 15% per annum	130	130	130
Sub-total	370	370	370
Total Manufacturing Costs	610	770	930
Desired Pretax ROI above interest @ 30% per annum above Manufacturing Costs	260	260	260
TOTAL REQUIRED REVENUE	870	1,030	1,190
Resulting Laminate Cost & Profit, \$/sq. meter (excluding materials handling costs and scrappage losses)	14.50	8.58	6.61

metal cleaning equipment is such that it could supply sufficient metal in one shift to support even three shifts of the laminating operation.

The estimated cost of laminating would add from \$6.60/m^2 to \$14.50/m^2 over and beyond the cost of contained materials, to the price a laminate user would have to pay for laminates. These batch laminating costs are not only very high in comparison to the cost of 0.8 mm sheet steel, but also to the cost of contained materials in a laminate of equivalent stiffness to 0.8 mm steel. The costs outlined are very sensitive to the assumed capital related costs. These costs could be significantly lower if used or depreciated equipment were available to a laminator.

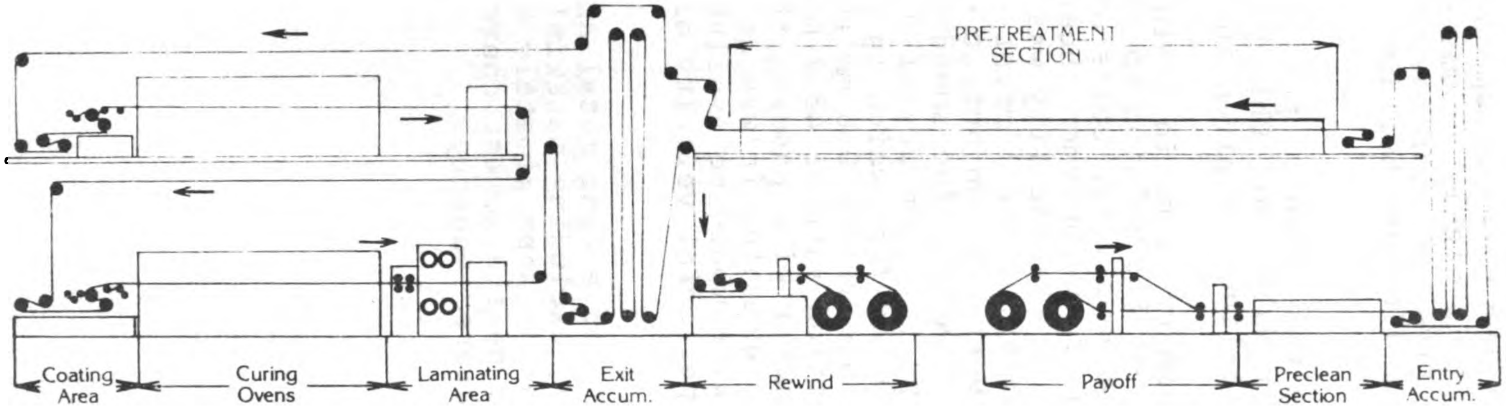
The output of laminate in the outlined process is determined by the time needed to heat and cool the platens. An alternate processing route as indicated in Figure D-1 would be to operate two presses, one operating hot and one operating cold. Conceptually a laminate sandwich would be placed between two steel sheets, or cowls, that are rigid enough to allow a laminate to be handled with minimum disturbance even when its core is molten. The cowls are placed in the first hot press which is closed for sufficient time to allow polymer to melt at the skin-core interface. The press is then opened and the cowl assembly is transferred to the second press operating at room temperatures, where the polymer cools and solidifies to form the product laminate. The advantages foreseen for this approach is that the cycle time for the process is reduced to that needed to heat or cool the cowls (which is of the order of 15 sec.-60 sec.), and greatly reduces energy requirements from that needed to heat and cool the platens to that needed to heat and cool the cowls. The major disadvantage of this approach is that it may not work since pressure is released during the time the core is in a molten state.

If this approach were to result in the manufacture of acceptable laminates, the production rate of 1 m x 3 m laminate sheets would increase by a factor of six over that assumed in the prior example. Average resistance time in the press would be decreased from 6 min to 1 min. Cost of lamination would be decreased by a factor of approximately three to four, as outlined in Table D-2. These costs are still high in comparison to the cost of 0.8 mm steel.

D-2 CONTINUOUS LAMINATION

Most of the difficulties encountered with batch lamination of metal-plastic laminates are eliminated in a continuous laminating operation. As outlined in Figure D-2, a laminate can be formed in a continuous manner by feeding a polymer sheet of metal, passing the assembly through a roll press or hip roll, where the hot metal comes into contact with the polymer sheets and causes it to melt at its surface, and then cooling the assembly to form

PRE FINISH METALS INC.
72" COIL COATING LINE



Pre Finish Metals' 72-in. coil coating line will begin at "payoff," at right, and will follow directions indicated by arrows, finishing at "rewind."

FIGURE D-3   PRE FINISH METALS INC. NO. 6 72 IN COIL COATING LINE

SOURCE : PRE FINISH METALS INC.

TABLE D-2

OPERATING COST SUMMARY - BATCH MANUFACTURE OF METAL-PLASTIC LAMINATE ON SEQUENTIAL PLATEN PRESSES

Shifts per day	1	2	3
Operating Hours per Year	2,000	4,000	6,000
Nominal Laminate Output, 10^3 square meters/yr	350	700	1,050
	Annual Costs, 10^3 $ / year		
<u>Direct Costs</u>			
Operating Labor: 6 men/shift @ $40K/m-yr	240	480	720
Utilities	10	20	30
Miscl. Supplies	10	20	30
Sub-total	260	520	780
<u>Capital Related Costs</u> (Capital Investment in Physical Plant: $1.35 Million)			
Depreciation			
Equipment @ 20% per annum	250	250	250
Buildings @ 5% per annum	5	5	5
Maintenance, Insurance, Taxes @ 10% of Plant Investment per annum	135	135	135
Interest on Capital Invested in Physical Plant @ 15% per annum	200	200	200
Sub-total	590	590	590
<u>Total Manufacturing Costs</u>	850	1,110	1,370
Desired Pretax ROI above interest @ 30% per annum above Manufacturing Costs	410	410	410
TOTAL REQUIRED REVENUE	1,260	1,520	1,780
Resulting Laminate Cost & Profit, $/sq. meter (excluding materials handling costs and scrappage losses)	3.60	2.17	1.70

APPENDIX D REFERENCES

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D-7 K. Taguchi, Plastics Dept., Mitsui & Co. (USA), Inc., New York, NY, Personal Communication, June 20, 1980.

D-8 H. R. Fisher, Arvinyl Division, Arvin Industries, Inc. Columbus, Indiana, Personal Communication, May 6, 1980.

APPENDIX E

REPORT OF INVENTIONS

After a thorough review of the work performed under this contract, no new innovations, discoveries, improvements or inventions were made or patents submitted.

The study did result in a better understanding of the potential of metal/plastic laminates towards reducing motor vehicle weight, as well as manufacturing feasibility and cost on a per-pound-weight-saved basis.