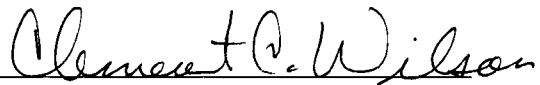
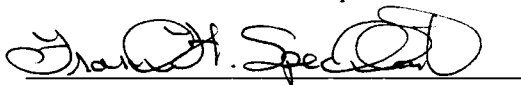


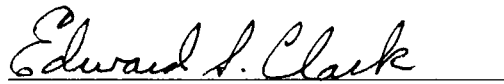
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**DESIGN OF SATURN AUTOMOTIVE PLASTIC DOOR PANELS FOR
ASSEMBLY**

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Barton Kirk Ideker

December, 1993

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ABSTRACT

This project was an investigation of new methods for attaching Saturn plastic automobile door panels to metal frames. The design emphasis was on assembly. The current Saturn door attachment process was considered too slow and labor intensive. Three new attachment schemes were devised--the sliding concept, the flexing concept, and quarter-turn fastener concept. The sliding and the flexing concepts were designed in detail, prototyped and tested. A detailed design was not necessary for the quarter-turn concept due to the commercial availability and wide-spread use of these fasteners. The sliding and flexing prototypes were refined to a level where assembly simulations could be timed with reasonable accuracy. The prototypes were not final designs ready for production. Testing involved assembling each design repeatedly and comparing the assembly times with those of the current attachment method. Also, the sliding prototype was subjected to rigorous force and creep or stress relaxation testing.

The sliding design appeared to be the superior concept both structurally and in terms of assembly time. It provided a more solid, stable attachment than the flexing concept and was easier and faster to assemble. Creep or stress relaxation of the plastic hooks used in the sliding design proved to be the major flaw at elevated temperatures. It was recommended that the flexing design be developed from a "clean sheet" approach instead modifying the current panel and frame.

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Chapter 1

Summary, Conclusions and Recommendations

Background

Project Description

Saturn is the first major car line that uses injection-molded thermoplastic vertical body panels. Consequently, little precedent or past design experience exists. An area that Saturn is attempting to improve upon is door panel assembly. Currently, the panels are attached by placing n-clips on the plastic panel, and then driving screws through holes in the metal door frame into the n-clips on the panel. A total of nine n-clip/screw sets are used on the driver's side SL2 door that was studied in this project. While this method of assembly is solid and meets all requirements, it is considered slow and labor intensive. Saturn is seeking new designs with shorter assembly times.

Design Descriptions

Following two months of conceptual designing, a thorough design review was performed with input from the Saturn engineers. Three concepts were selected from that review and two were prototyped in detail for this project. The designs are briefly described below.

The **sliding design**, presented in chapter 5, consists of a series of plastic hooks molded into the back of the plastic door panel. Each hook mates with a slot in the door frame. The panel is aligned and each hook slides into its corresponding slot. As the hook slides down the slot, it acts as a deflected cantilever beam that provides clamping force to resist vibration and to hold the door tightly against the panel. The hooks are

designed to allow vertical and horizontal adjustments so that the door can be aligned with neighboring panels. Finally, two fasteners are placed in opposite corners of the door to provide location and security against theft. This design was prototyped and tested.

The **flexing design**, presented in chapter 4, takes advantage of the plastic door panel's ability to bend. First, sheet metal clips are attached to the inside of the door panel and brackets are welded to the door frame. Next, the panel is bent with a flexing device and the clips on the panel are aligned with the brackets on the frame. Then, the panel is slowly relaxed to its normal position. As it expands, the clips on the panel mate with the brackets on the frame and the door is held in position by a pre-load. The pre-load can be supplied by the panel if it is not fully expanded or by the clips if they are deflected. This method was also prototyped and tested.

The other promising concept is the **quarter-turn fastener**, discussed in chapter 3. It is a mechanical fastener, usually made of metal, that is intended to replace the nine n-clip/screw fasteners one for one. The quarter turn fastener is intended to be inserted into a slot in both the frame and panel. The end of the fastener is designed to provide a spring load that, when turned 90°, holds the panel against the frame. It was not prototyped because it is already commercially available and widely used. Instead, the bulk of this project's time and resources were spent on the flexing and sliding designs.

Conclusions

Prototype Results

The sliding design prototype provided a solid attachment and met all requirements except for creep or stress relaxation. When loaded slide hooks were placed in convection testing ovens at elevated temperatures the plastic material relaxed. The hooks failed in less than 24 hours at 180° Fahrenheit. Failure in these tests occurred

when the clamping force decreased below 0.75 lbs. At 130° Fahrenheit, the hooks relaxed but did not weaken below the required clamping force for the duration of the test, 48 hours. The prototypes were milled from a block of unmodified acrylonitrile-butadiene-styrene (ABS). The SL2 door is made from a polyalloy blend of ABS and polycarbonate (PC) that has superior thermal properties. Further relaxation testing should be performed on slide hooks manufactured from the ABS/PC blend actually used in the door before this design is modified. However, if relaxation is a serious design flaw, then the clips can be made from a creep resistant material and inserted into the mold in the manufacturing process. Also, the vibrational characteristics of the slide hooks must be tested extensively. They were not tested on this project due to the lack of testing facilities.

Results of the flexing design prototype were not as promising as those of the sliding design. The flexing prototype did not provide a solid attachment. At the lower-rear edge, a force of less than ten pounds could separate the panel from the frame. The front and rear flanged ends were sawed off because they acted as stiffeners, resisting panel deflection. Consequently, the flexing design can not be developed without a major redesign of the panel architecture to remove the flanged ends. Also, the flexing design clips only secure the upper and lower edges of the panel, so fasteners will be required for the middle-front and middle-rear edges. A minimum of three fasteners and as many as five may be necessary to secure the panel properly.

Flexing devices are needed to remove and install the panel so each Saturn dealership and body shop would need a manual flexing device and the assembly plant in Spring Hill, Tennessee would need an automated flexing machine. The flexing machine does offer one advantage over the sliding design and current assembly method--it can be designed to flex and support the door during installation; thereby, eliminating all physical

strain from the operator. A prototype flexing device was constructed and used in assembly testing.

Assembly Times

Both the sliding design and the flexing design have significantly lower assembly times from the current attachment process. The sliding design had the quickest prototype assembly time. It was, on average, 96.5 seconds faster than the current process and 11.6 seconds faster than the flexing design. The results and a statistical breakdown of prototype assembly testing are listed in Appendix E. Figure 1.1 is a bar chart comparing Boothroyd and Dewhurst design for assembly (DFA) worksheets, prototype assembly test averages, and projected production assembly times for the three attachment methods. The DFA worksheet estimates were within 7% of the actual prototype assembly results. Projected production assembly rates are based on prototype testing and redesign recommendations.

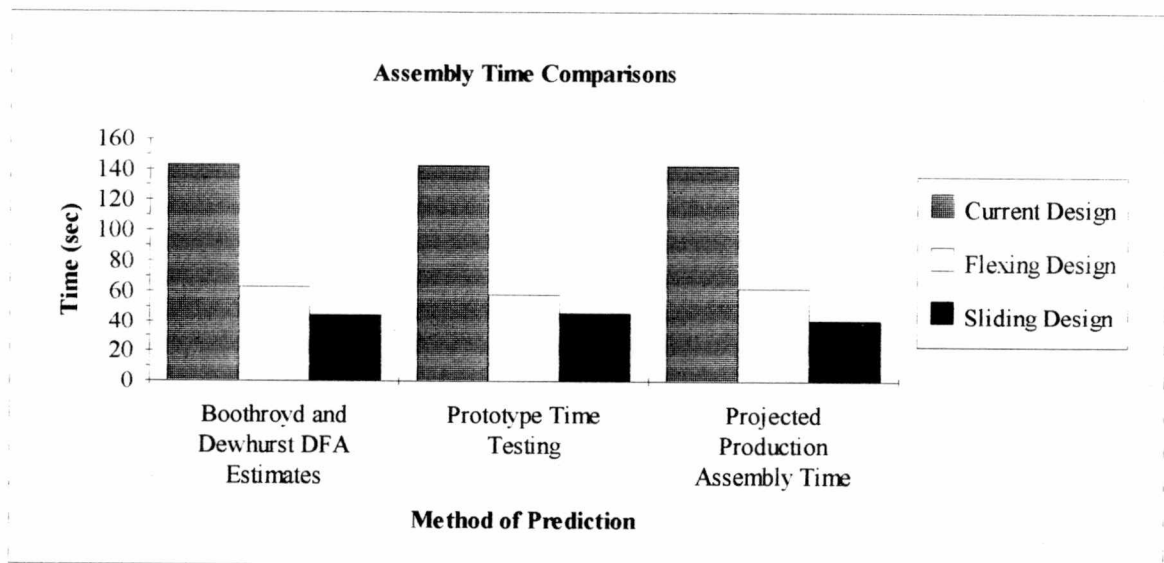


Figure 1.1 Assembly Time Comparison Bar Chart.

Recommendations

Both the sliding design and the flexing design are improvements over the current method of attachment. The sliding design is easier to develop for production with the current door and panel configuration. However, for a long-term solution, it may be possible to develop a flexing design that is preferred over the sliding method.

The sliding design should be developed for production of because it is superior to the current design and the flexing design. It is over ninety-five seconds faster than the current design and requires only two fasteners. If the relaxation problem can be solved, the sliding concept should be able to meet all other requirements. It is simple, it does not require special tools, and it eliminates eight fasteners from the current attachment method. At current production levels, the sliding design will save over \$800,000 per year in labor costs (based on a \$35/hr labor and overburden rate). It will also save over \$1,600,000 annually in screw/n-clip fasteners (based on a total cost of 20¢ per fastener set). The mold redesign will not be significantly more difficult than the present mold because the flanges will be eliminated and replaced with slide hooks. See chapter 5, the sliding design chapter, for more information and recommendations.

Should the sliding design fail due to creep or relaxation in the hooks, the flexing design is another alternative to the current assembly method. The flexing design will cut the assembly time by over 80 seconds per door. It will also eliminate between four and six fasteners. If a stable, solid attachment can be achieved with a flexed panel, it will save over \$700,000 per year in labor. Furthermore, between \$720,000 and \$1,080,000 can be saved annually in material costs by eliminating the four to six fasteners per door.

Both the sliding and flexing designs will require a great deal of resources for development. Complex molds must be fabricated, and a copious amount of redesign and testing will be necessary before either of the proposed designs can replace the current

assembly method. The sliding design will be easier to develop and mold than the flexing concept. In sum, the sliding method of attachment saves significant assembly time and material over the current design and the flexing method, and it will be easier and less expensive to develop (for the current door panel style) than the flexing method. For a long-term solution, the flexing design should be developed from a "clean sheet" approach without using the current door panels for prototyping. This may lead to the best method of door attachment.

Chapter 2

Project Description

Introduction

Saturn's plastic body panels

General Motors' revolutionary Saturn division is the first major car maker to utilize plastic automobile panels on a large scale. Currently, Saturn manufactures nineteen different vertical body panels (doors, fenders, rear quarter panels, facia, etc.) exclusively from plastic [Mahoney, 1993]. Why plastic? Because it offers superior corrosion and impact resistance, as well as being lighter than steel for improved fuel economy. In fact, one of Saturn's advertised features is the impact resistance of its doors to shopping carts in grocery store parking lots. Unfortunately, large horizontal body panels (hood, roof and trunk) are still made of steel "because they are more visible (hood, in particular) and because they can distort under their own weight or from temperature changes" [Charrier, 1991].

Plastic body paneling is a relatively unexplored automotive technology, and, consequently, new testing standards, painting techniques, and attachment methods must be developed or perfected. In fact, Saturn design engineers developed product assurance tests simultaneously with the design of each plastic body panel because no standards existed for similar injection molded panels within General Motors [Quinlan, 1993]. This thesis project involves developing new fastening technology for the attachment of plastic vertical body panels to metal door frames. The focus is on the drivers-side front door of a Saturn SL2 model because this door has a considerable number of service and assembly

constraints. The SL2 door panel and frame are shown in figure 2.1. All Saturn door panels are made of a acrylonitrile-butadiene-styrene (ABS), polycarbonate (PC) polyalloy. The ABS/PC blend provides superior impact resistance desired in a car door.

History of Plastic Body Panels

Plastic automobile body panels first appeared in the mid 1950's with the General Motors' Corvette. Early panels were made of fiberglass or fiber-reinforced plastic (FRP). In the 1960's, the Citroen Mehari, an inexpensive French vehicle, made extensive use of thermoformed ABS body panels [Charrier, 1991]. The Pontiac Fiero body produced during the mid 1980's was almost entirely fabricated from sheet molding compound (SMC), a somewhat brittle thermoset. The above mentioned automobiles

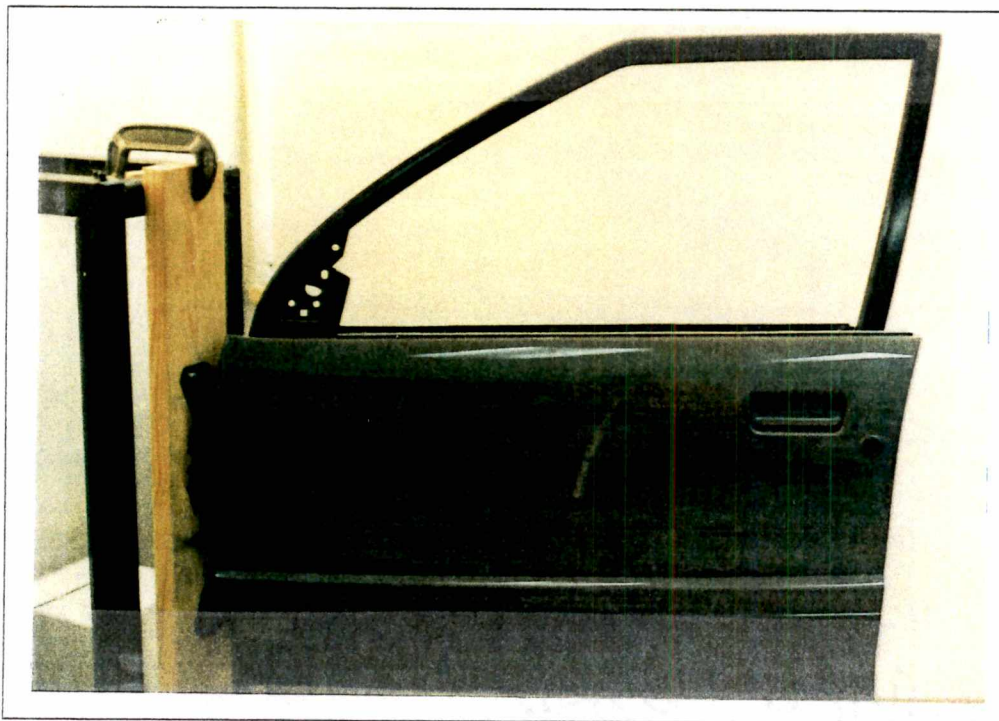


Figure 2.1 - Saturn SL2 door panel and frame.

were expensive sports cars or small production "experiments". Saturn is committed to broad, long-term use of injection molded thermoplastics in all of its vertical body panels.

Over the past two or three decades general plastics use in the automotive industry has exploded in both volume and sophistication [Charrier, 1991]. If polymer body panels are proven economically viable on a large scale such as the Saturn line, the rest of the industry will follow Saturn's lead, sending steel body panels into obsolescence.

Need for New Panel Attachment Methods

One of the major shortcomings of the plastic door panel is the method of attachment to the steel frame. The current method of attachment at Saturn is considered far too labor intensive. Traditional steel panels are typically crimped and then spot welded onto the frame with industrial robots, while Saturn uses a two piece n-clip/screw fastener at various locations around the plastic panel. The SL2 door panel requires nine (9) sets of these n-clip/screw fasteners -- all fastened by hand. If a new system of connection can be developed that eliminates most or all of these n-clip/screw fasteners, it will greatly reduce the amount of labor in each automobile. For example, assuming Saturn spends \$35/hr including overhead for skilled labor, the elimination of one minute of labor per door amounts to an annual savings of over \$500,000 at current production levels. If a labor saving attachment method can be developed that is applicable to all 19 vertical body panels, the benefits will be tremendous.

Current Saturn Assembly Process

The door panels are currently fastened to a painted metal frame via nine (9) pairs of screws and floating threaded n-clips. The assembly operation begins when the plastic body panels enter the main assembly building on a paint fixture. The complete set of

body panels for a single car is painted on a fixture to insure that the colors match precisely. The door panels are removed from the fixture, prepared for attachment, and sent to an area where the car is the final stages of assembly. The following is a detailed chronological description of this procedure:

1. The painted panel is removed from the paint fixture and placed on an assembly fixture.
2. Vibration absorbing foam tape is placed on the inside of the ABS/PC door panel.
3. Nine (9) threaded, floating clips are placed over molded holes and slots on the inside of the panel.
4. Keyhole/lock (one piece) trim is pushed into the lock hole in the panel.
5. The door panel is placed on a cart and transported to main assembly line where the car is in the final stages of production.
6. The door panel is placed on the door frame which is already attached to the car.
7. Two (2) clamps are placed on top of the panel/frame interface to hold the panel against the frame during assembly.
8. Nine (9) screws are driven through blind holes in the sheet metal frame and into the floating clips attached to the door panel.
9. The two (2) clamps are removed from the top on the assembled door.

Project Goals and Requirements

Design for Assembly (DFA) -- Goals for Project

Assembly is the primary thrust of this product redesign. There are several approaches to lowering the amount of labor in the door such as replacing the screw/clip fasteners with similar mechanical fasteners, redesigning the frame and/or panel, affixing

with adhesives or other non-traditional fastening methods. The following guidelines adapted from the design for manual assembly chapter of "Assembly Automation and Product Design" [Boothroyd, 1992] can be directly applied to this project:

- A. Minimize number of parts.
- B. Minimize number of fastening points.
- C. Eliminate screwing operations (slowest method of fastening).
- D. Use parts that are easy to handle (i.e. not too small, do not tangle).
- E. Use parts that are easy to insert and fasten.
- F. Eliminate need to clamp door to frame for assembly.

Specifications and Constraints

A complete list of Saturn and Superior Engineering Design Program (SEDP) specifications for the door panel is listed in Appendix A. Table 2.1 is a Middendorf "needs analysis" for the primary specifications and constraints [Middendorf, 1990]. A few specifications are unique to the door panel such as the requirement that the panel fasteners be removable and reusable. This is necessary because the inner workings (window, lock, audio speakers) of the door are serviced by removing the outer door panel as opposed to traditional door service from the inside of the car. Several of the designs presented in chapter 3, the conceptual design selection chapter, do not meet the removable or reusable requirements, but are included because they may be adaptable to other Saturn plastic vertical body panels that do not require removal for service.

Table 2.1 - Door Panel Needs Analysis		
Phase	Requirements Goal, or Preference	Needs
Production	R	Fasteners should be easily accessible
Production	R	Reduce number of parts from current design (eliminate fastener or make one piece fastener)
Production	R	Eliminate screwing operations
Production	R	All fastener parts should be easy to handle
Production	R	Fastener finish requirement - exposed surface - GM 6138M Black
Production	R	Door Panels shall meet Saturn gaps and flushness criteria per exterior panel sections
Production	P	Fasteners should be common throughout entire vehicle (common to other panels)
Production	P	Eliminate door clamping during assembly
Production	G	Use minimum number of fastening points
Consumption	R	Attachment should allow door to "grow" thermally across mating steel flange
Consumption	R	Panels should avoid squeak, rattle and wind noises
Consumption	R	Normal towing of vehicle should not damage attachment
Consumption	R	Door attachment shall pass door structural slam tests as stated in product specifications
Consumption	R	Mechanical fasteners must be removable for service using common hand tools
Consumption	R	Mechanical fasteners must be reusable
Retirement	P	Door panel shall be easily removable for "clean stream" recycling purposes

Chapter 3

Conceptual Designs

Fasteners

Introduction

This section concerns conceptual designs of mechanical fasteners that can replace the current fasteners and reduce assembly time without major panel redesign. The current attachment method of screwing is the slowest mechanical fastening method of assembly [Boothroyd, 1992]. The simplest way to reduce labor cost in the Saturn door panel assembly is to replace the screw/j-clip system with a one-piece fastener that does not require screwing. This modification would lower the number of parts and assembly steps by eliminating the nine (9) j-clips. Unfortunately, all fasteners associated with the door must be removable and reusable which eliminates many solutions such as annular snap fits and rivets. However, Saturn is looking for "fresh concepts" for all kinds of body panel attachments. Therefore, some non-removable/reusable concepts are included in this chapter in hopes that they may prove useful for attaching other body panels such as fenders and quarter panels that do not require access for service.

Quarter-turn Fastener

Figure 3.1 is a sketch of a quarter-turn fastener. It is designed to be inserted into a slot of equal size in the frame and panel and turned 90° to lock it in place. The fastener can be made out of metal for high strength. The end of the quarter-turn fastener, made of

Quarter Turn Fastener Concept

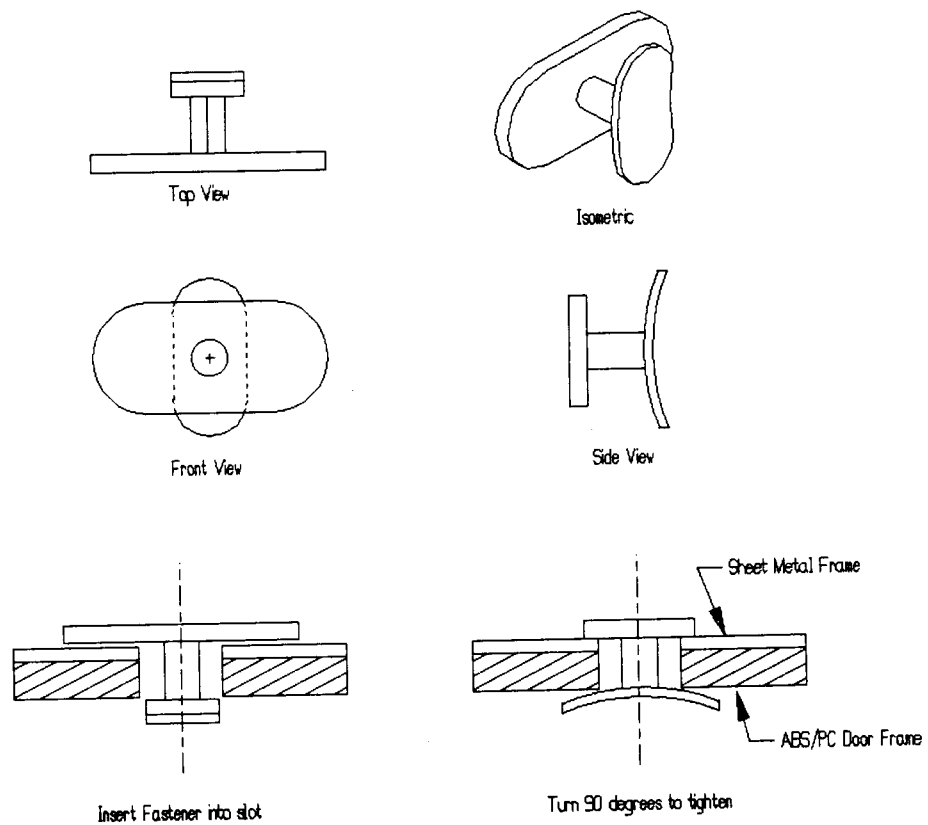


Figure 3.1 - The Quarter-Turn Fastener

spring steel, is slightly smaller than the slot, and therefore able to be inserted through the slot. Once inserted, it is turned and locked into a groove molded into the plastic panel. The shape and material at the end act as a spring to provide the necessary clamping force. This design reduces the number of parts by eliminating the need for the nine threaded j-clips. It eliminates the screwing process and, conceptually, is easier to insert and align. The quarter-turn fastener is intended to be removable with common hand tools and reusable for service requirements so that it meets all specifications for the door panel fasteners.

Blind Rivet Fastener

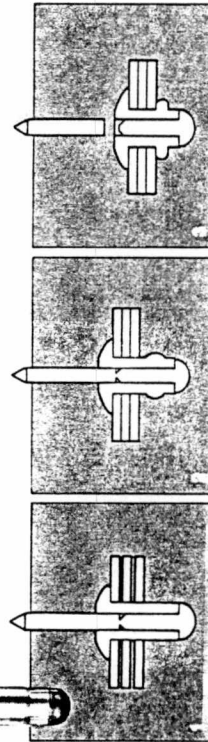
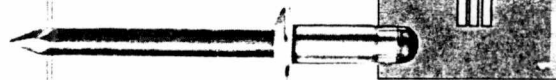
An industrial blind rivet such as the Avdel Structural Avex®, shown in Figure 3.2, which offers a wide panel grip range and compensates for oversized, irregular, or misaligned holes is ideal for attaching a plastic body panel to a metal door frame. Like quarter-turn fasteners, rivets eliminate the need for a threaded floating clip. They are strong, resist vibration, and are commonly used in other automobile door applications such as speaker attachment. These rivets are commercially available and offer a quick, easy alternative to the screw/clip fasteners.

Blind rivets do not meet Saturn door panel specifications because they are not easily removable and are not reusable, but rivets are an economical alternative to the screw/j-clip fasteners on other body panels such as fenders and quarter panels. Experiments have been performed for this project with small aluminum rivets joining pieces of the ABS/PC door panel and sheets of aluminum of approximately the same thickness as the steel door frame. These tests indicate that the rivet head can be drilled off with a drill bit slightly larger than the mandrel. The drilling does not damage the ABS/PC door panel material or the metal frame. If a quarter panel or fender is damaged

Structural Avex®

High Strength, Blind Riveting System

- ☐ All Steel Construction.
- ☐ Low Profile Head.
- ☐ Diameters 1/8, 5/32, and 3/16".
- ☐ Exceptionally high strength values.



PRODUCT FEATURES & BENEFITS

- Low profile head enhances product appearance.
- Multi-grip capability reduces inventories and possibility of selection error.
- Large concentric tailside formation compensates for oversized, irregular, or misaligned holes.
- Clamping force eliminates gaps for vibration-proof joint.
- Stem breaks flush or just below head. No secondary operations required.
- Blind installation reduces in-place assembly costs.

Figure 3.2 - The Blind Rivet

Source: Avdel brochure no. 1MB/SA0486 10M-5. Parisippany, NJ. 1984

and must be replaced, the rivets could be replaced with screw/clip fasteners by the service technicians. This method allows for fast assembly and does not affect the majority of cars--only those needing body work. Therefore, blind rivet attachment is strongly recommended for body panels that do not require removal for service.

Removable Rivet Fastener

A fastener similar to the ITW Fastex® removable rivet, shown in Figure 3.3, may be used to attach the panel to the frame. The removable rivet offers a simple, easy to assemble, remove and reuse alternative to the screw/clip fasteners used currently. Unfortunately, the only material capable of high deflections in short lengths is plastic because the relatively low flexural modulus of plastics allows for large deflections. Plastic has two significant weaknesses--poor strength characteristics and creep or stress relaxation over time. A material such as Polyoxymethylene (POM), better known as acetal or Delrin® might work. It is highly water resistant, heat resistant, creep resistant, and well known for its "springy" property. Removable rivets made of acetal are commercially available. Two other concerns associated with removable rivets are that they may not "grip" the panels well enough to meet Saturn needs and that they require a preload of some sort to avoid rattling with vibration.

Fastener Concept Evaluation

The purpose of this project is to reduce the amount of labor required to attach a plastic panel to a car frame; therefore, an evaluation tool is needed to compare prospective conceptual designs for manual assembly efficiency. Assembly times for the conceptual fastener designs mentioned above can be compared with the current Saturn fasteners using the Boothroyd and Dewhurst classification system for manual assembly

REMOVABLE RIVETS

The removable rivet is a one-piece unit that is quickly installed by hand or with automatic equipment. It is ideally suited for applications where access to the back of the panel is impossible. The rivet is removable and re-usable by using the tip of a thin, blunt-pointed instrument to depress the center of the rivet and release the locking mechanism. Removable rivets are manufactured in a black polyacetal material.

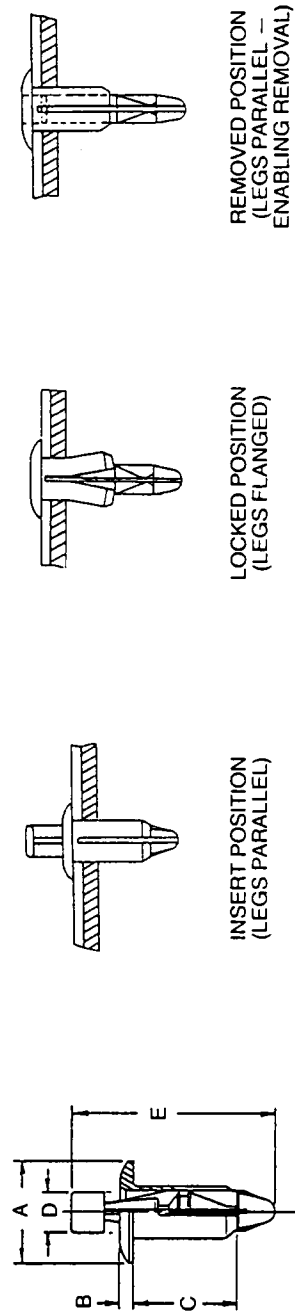


Figure 3.3 - The Removable Rivet

Source: ITW Fastex® 1992 Catalog. Revision #2. Page 4.

[Boothroyd, 1992]. With this method, two-digit codes are used to quantify the duration for each assembly step. While the estimated current Saturn assembly time may not accurately reflect the actual process time, Boothroyd and Dewhurst DFA time estimates provide the means for comparison of different concepts to the original design with assembly times that should be accurate, relative to one another, thus giving an objective method of evaluation. Prototype testing found the Boothroyd and Dewhurst DFA estimates to be within 7% of actual assembly time. All other variables (number of fastening points, the use of assembly clamps, etc.) are the same so that only the fastener types vary.

Table 3.1 is a sample Boothroyd and Dewhurst DFA worksheet for the current Saturn process. Each assembly step is listed with its Boothroyd and Dewhurst code and quantified with an assembly time and the labor cost is calculated assuming a \$35/hr rate. All Boothroyd and Dewhurst DFA analysis worksheets used to generate these numbers are included in Appendix B.

Table 3.2, an assembly time comparison of the three fastener concepts with the original screw/clip fastener, clearly shows that the Quarter-turn, Removable Rivet and Blind Rivet all save a significant amount of labor. If 60 seconds or more can be cut off the current assembly time without sacrificing structural and vibrational integrity, it will save Saturn over \$500,000 dollars per year at current production levels.

Another useful evaluation tool is the Pugh concept evaluation matrix--an unweighted matrix that compares new concepts with a datum design [Pugh, 1990]. In this case the datum is the current Saturn fastener. If a design criterion listed on the matrix is superior to the datum, a plus sign (+) is placed in the design column, if the criterion is similar to the datum it is given an "s" meaning same, and if the criterion is inferior a minus sign (-) is placed in the concept's column. When all criteria are rated,

Table 3.1 - Sample Boothroyd and Dewhurst DFA Worksheet								
Item #	Item Name and Assembly Description	Number of Parts	Handling Code	Handling Time (sec)	Insertion Code	Insertion Time (sec)	Total Time (sec)	Total Cost (cents)*
1	Floating Clips - Attach to Panel	9	20	1.8	30	2	34.20	33.25
2	Door Panel - Place on frame	1	96	4	12	5	9.00	8.75
3	Clamps - Clamp panel to frame	2	00	1.13	00	1.5	5.26	5.11
4	Screws - Drive into floating clips	9	10	1.5	39	8	85.50	83.13
5	Clamps - Remove from door	2	00	1.13	00	1.5	5.26	5.11
Grand Totals							139.22	135.35

* Based \$35.00/hr. labor rate.

Table 3.2 - Fastener Assembly Time Comparisons.				
Criteria	Current Saturn Design	Quarter-turn Fastener	Blind Rivet	Removable Rivet
Assembly time (s)	139.2	78.0	90.1	81.1

the +s, -s, and s' are summed beneath the matrix and the overall concepts are evaluated. The Pugh matrix for fastener concepts, Table 3.3, indicates that the quarter-turn concept is the superior design.

The quarter-turn fastener concept is the best replacement for the screw/clip fasteners currently used. The Pugh matrix shows that it has fewer limitations and the same number of advantages as the other two fastener concepts. Also, the blind rivets are not acceptable in the door panels because they can not be removed with common hand tools and they are not reusable. The removable rivet design is a weak concept because of the many structural and vibrational questions associated with using a plastic fastener in such a demanding environment.

Nontraditional Fastening Concepts

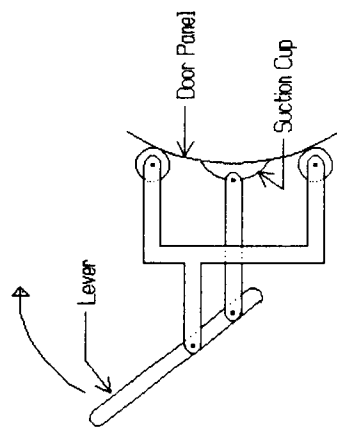
The previous section concerned new fastener ideas that would simply replace the existing fasteners without reducing the number of fasteners required to hold the door. The following concepts are intended to reduce or eliminate the need for mechanical fasteners by non-traditional fastening means.

Flexing Concept Description

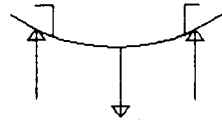
The flexing concept, shown in Figure 3.4, uses a "flexing device" to bend the door panel. A series of clips protrudes from the back side of the panel that are intended to hold the panel against the door frame when mated with brackets in the frame. While the door panel is deflected, it is intended to be aligned with the door frame and released so that as the panel expands to its original shape, the clips move onto brackets in the door frame. This attachment provides clamping strength and holds the panel firmly against the frame. Several mechanical fasteners may be necessary to locate the panel exactly and

Table 3.3 Pugh Fastener Evaluation Matrix				
Concept/Criteria	C u r r e n t P r o c e s s	Q u a r t e r T u r n	B l i n d R i v e t	R e m o v a b l e R i v e t
Assembly Time		+	+	+
Easily Accessible		s	s	s
Easily Handled Parts		s	-	-
Life in Service	D	s	s	-
Minimum # of Fastening Points	a	s	s	s
Minimum # of Parts	t	+	+	+
Need for Additional Pre-loading	u	s	s	-
Need for Panel/Frame Redesign	m	-	s	s
Part Cost		+	+	+
Removable		s	-	s
Reusable		s	-	s
Sum of the +'s		3	3	3
Sum of the -'s		1	3	3
Sum of the same		7	5	5

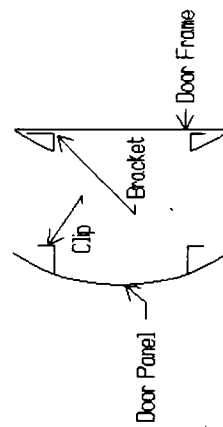
Panel Flexing Concept



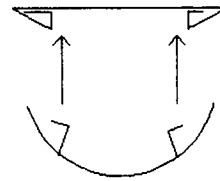
Flexing Device



Flexing Forces



Unmated/Unflexed Parts



Flexed Panel



Mated Parts

Figure 3.4 - The Flexing Concept

provide security so that the panel cannot be removed from the outside of the car. Also, fasteners are required to hold the middle of the panel against the frame because the clips and brackets are all located at the top and bottom of the frame.

This concept reduces labor and parts by eliminating at least four fasteners, and, perhaps as many as seven. The design also exploits a major advantage of plastic, its flexibility. Unfortunately, with the current SL2 door design, the flexing concept will not work because the rear of the door cannot bend. The flanges around the door act as stiffeners to resist bending; however, this problem can be corrected in future models by eliminating the large flange sections currently used to hold the screw/n-clip fasteners. The flexing concept is discussed in detail in chapter 4.

Sliding Concept Description

The sliding concept employs a series of "hooks" that are injection molded into the back of the door panel to clamp the panel to the frame. Figure 3.5 is a conceptual sketch of the hook and Figure 3.6 shows the sliding mechanism at work. During stamping of the sheet metal door frame, a series of holes with tabs is punched and bent at locations opposite the injection molded hooks on the panel. The door is assembled by sliding the panel down over the frame and allowing the sheet metal tabs to deflect the injection molded hooks, which, acting as cantilever beams, produce a clamping force sufficient to resist vibration. Finally, two fasteners are inserted into the assembly for panel location and security purposes. This design will not work on the current SL2 door because a door latch protrudes through the panel, interfering with the desired sliding motion, but future models could be redesigned to avoid this problem by recessing the latch and allowing the handle, which attaches to the latch, to protrude through the door panel and be affixed after panel assembly. The sliding design is discussed in detail in chapter 5.

Slide Hook

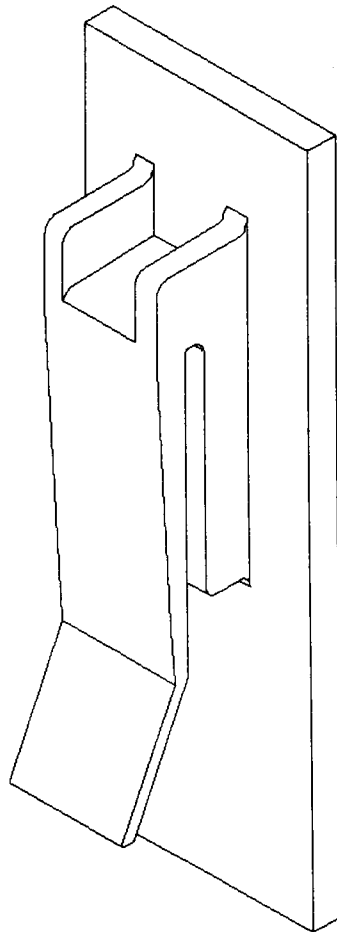


Figure 3.5 - Hook for Sliding Concept

Sliding Mechanism

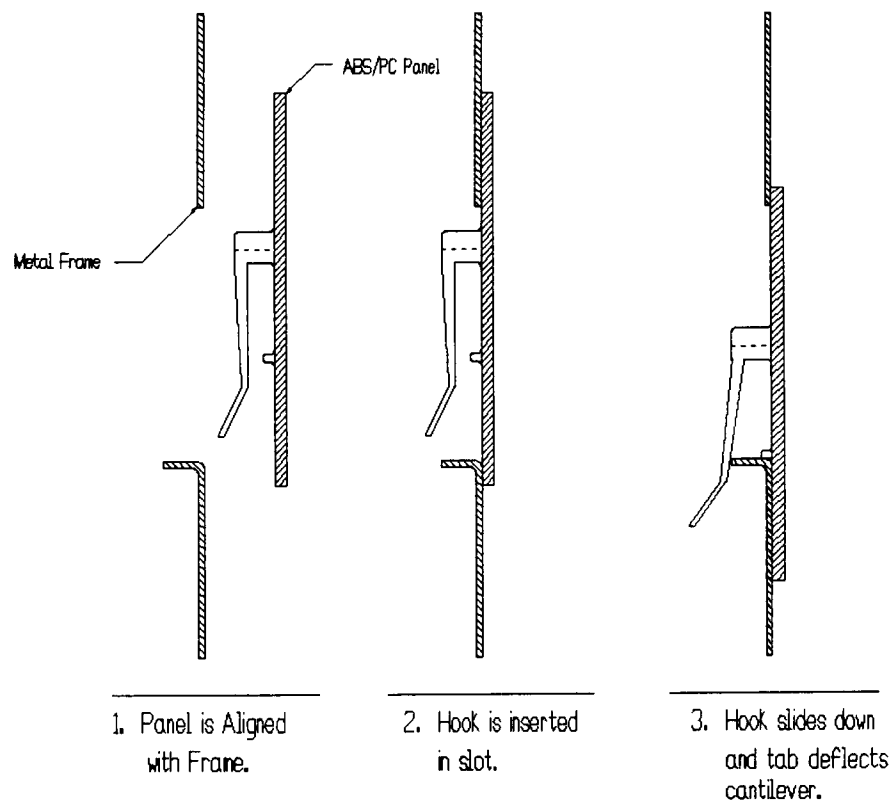


Figure 3.6 - Sliding Mechanism

Overall Conceptual Design Evaluation

The following is an evaluation of the concepts warranting further investigation-- the quarter-turn fastener, the sliding concept and the flexing concept. Table 3.4 is a Pugh matrix for the three final concepts. The sliding design is rated the highest followed by the flexing concept and the quarter-turn fasteners. According to the Boothroyd and Dewhurst DFA worksheet results, shown in table 3.5, the sliding and flexing concepts could be assembled in half of the time needed to attach a panel currently -- 50% faster. The quarter-turn fastener was projected to be 38% faster than the current attachment method. It was therefore decided that the majority of design time should be spent on the sliding and flexing concepts because they are the most promising and because they required the most development. Prototypes of the sliding and flexing concepts were designed and tested for this project. The quarter-turn fastener was not developed because similar fasteners are commercially available and widely used. Pros and cons of each concept are listed on the following pages.

Quarter-turn Fasteners

On the basis of the evaluation results from the fastener section of this chapter, the quarter-turn design appears to be the most promising solution to replace the screw/j-clip fasteners currently used. Many variations of the quarter-turn fastener are available commercially so a design can be adapted from a competitive analysis of the existing fasteners rather than developing a new fastener from scratch.

Pros

- Simplest solution--need only to replace holes with properly sized slots in frame and panel.
- No strength/creep problems associated with plastic parts.

Table 3.4 - Pugh Concept Evaluation Matrix				
Concept/Criteria	C u r r e n t	Q u a r t e r	F l e x i n g	S l i d i n g
	P r o c e s s	T u r n	C o n c e p t	C o n c e p t
Additional Tools for Assembly		s	-	s
Additional Tools for Service		s	-	s
Assembly Time		+	+	+
Ergonomics of Assembly		s	+	+
Life in Service	D	s	s	-
Material Cost	a	+	+	+
Minimum # of Fastening Points	t	s	s	s
Minimum # of Parts	u	+	+	+
Number of Fasteners	m	s	+	+
Panel Easy to Align and Insert		s	s	s
Panel Easy to Handle		s	s	s
Removing - Ease of		s	-	+
Reusable		s	s	s
Sum of the +'s		3	5	6
Sum of the -'s		0	3	1
Sum of the same		10	5	6

Table 3.5 - Concept Assembly Time Comparisons				
Criteria	Current Saturn Design	Quarter-turn Fastener	Flexing Concept	Sliding Concept
Assembly time (s)	139.2	78.8	62.6	44.6

Cons

- Longest projected assembly time of the three final concepts, but still saves 59¢ of labor per door over the current assembly method for an annual savings of approximately \$500,000.

Flexing Concept

With the current SL2 door design, the flexing concept will not work because the rear of the door cannot bend; however, if the flanged stiffeners are eliminated from the front and rear edges of the door, it will flex without resistance.

Pros

- Solution is unique to industry.
- Does not require clamping during assembly.
- Boothroyd and Dewhurst DFA projected labor savings of 75¢ per door for an annual savings of over \$670,000.
- With a mechanical flexing machine at the assembly plant in Spring Hill, this design would transmit less physical strain to a worker than the sliding or quarter-turn concepts.

Cons

- Can not work on current door design because rear of door will not bend as needed.
- May not eliminate as many fasteners as the sliding design.
- Requires the design and distribution of a special tool, a flexing device, to all body shops and Saturn dealers. Also, requires a potentially expensive flexing machine for the assembly plant in Spring Hill.

Sliding Concept

The sliding concept is the best all around idea in both estimated assembly time and ease of service. The sliding mechanism was intended to be used in both the flexing and sliding concepts so the sliding concept took first priority for development.

Pros

- Requires only two fasteners.
- Can be serviced without special tools.
- Projected savings of 92¢ per door for an annual savings of over \$820,000.

Cons

- May be difficult to injection mold slide hooks on panel.
- Plastic may creep or fatigue over time.
- Can not slide on current SI2 door because of latch interference.

Chapter 4

Flexing Design

Design Description

Theory of Operation

The flexing design takes advantage of the plastic door panel's flexibility. Figure 3.4, from the conceptual design chapter, illustrates the concept. First, the panel is bent as shown with a flexing device. Once deflected, clips attached to the inside of the door panel are aligned with slots or brackets in the door frame. Next, the panel is slowly released. As the panel expands to its natural position, the clips on the panel mate with the brackets in the frame, and a pre-load, provided by the clips or by the panel itself, pulls the panel tight against the frame. Finally, fasteners are used to provide the panel with final location after adjustment and to secure the middle section of the panel. In this chapter, the term "clip" refers to any protrusion from the back of the plastic panel used for attachment, and the term "bracket" refers to any part of the door frame intended to mate with a "clip" for attachment purposes. The methods of pre-loading with the clip or panel are explained below.

The two methods of holding the clips against the bracket are clip pre-loading and panel pre-loading. With clip pre-loading, the panel is completely expanded to its relaxed position and the clips are held against the brackets by deflecting the clips. With panel pre-loading, the clips are stiff (they do not deflect), and the panel provides the force to hold the clips against the bracket by remaining partially deflected--not completely relaxing to its original position. Clip pre-loading was used in the prototype.

Design Limitations

The flexing design requires that the entire panel bend. Unfortunately, with the current SL2 door shape, the rear of the door can not bend. The flange used to receive the n-clips acts as a stiffener. The front of the panel is also stiffened by a smaller flange, but it can bend slightly. Both flanges must be eliminated, if the flexing concept is to be developed. During prototype construction, the flanged ends were simply sawed off. Saturn could redesign the door and eliminate the flanged ends for its next major model change.

Another weakness of the flexing concept is the need for mechanical fasteners. The prototype design requires the same fastening method along the top of the door--a molding strip along the top edge and a fastener in the upper-rear corner. Also, fasteners are needed along the middle edges of the door because the clips are only located on the top and bottom of the panel. At least one fastener will be required on the left and right edges of the middle of the panel. On the prototype, the bottom edge was the only surface truly held by the clips, without fasteners. The total number of fasteners could not be determined from prototype testing because the edges of the panel were sawed off. However, a minimum of three fasteners is required for this design, and as many as five or six may be necessary.

Operating Space and Design Constraints

The constraints for the flexing design are vertical travel, holding force and spatial clearance inside the frame. Vertical travel is the distance that the panel can move, up or down, for adjustment purposes while maintaining an acceptable holding force between the panel and frame. The vertical travel is limited in this design because the clips must be deflected a specified amount for spring force. Consequently, the panel can be

adjusted only slightly in the vertical direction without affecting the spring or holding force. Holding force is the force required to hold the panel against the frame. The prototype flexing design utilizes four clips along the bottom of the panel, and each clip must hold a minimum of 15 lbs. to insure a solid connection between the panel and frame.

The final constraint is the spatial clearance. The clips must clear the upper and lower brackets for insertion when the panel is deflected. When the panel is released and it returns to its natural position, the clips must contact the brackets and deflect slightly to hold the panel snugly against the frame. It was very difficult to construct a clip with the proper geometry that could be inserted between the brackets and then "catch" on the brackets after the panel is expanded. Most clip designs were too long and interfered with insertion or were short enough for insertion, but not long enough to catch the clip and hold the door on after the panel was relaxed. The clips on the panel tend to rotate and move backward, away from the frame, as the door is deflected. The design of the clip geometry is discussed in detail in the prototype section of this chapter.

Prototype Testing Results and Observations

Prototype Description

The prototype for the flexing design was fabricated by modifying an existing door panel and frame. Also, a flexing device was constructed from scratch. The Panel and Frame are pictured in figures 4.1 and 4.2, respectively. The flexing device is shown in figure 4.3.

The flexing device frame was primarily constructed with 2x4 lumber. It used a high-power suction cup with a built-in pump to provide the pulling force, while four 2

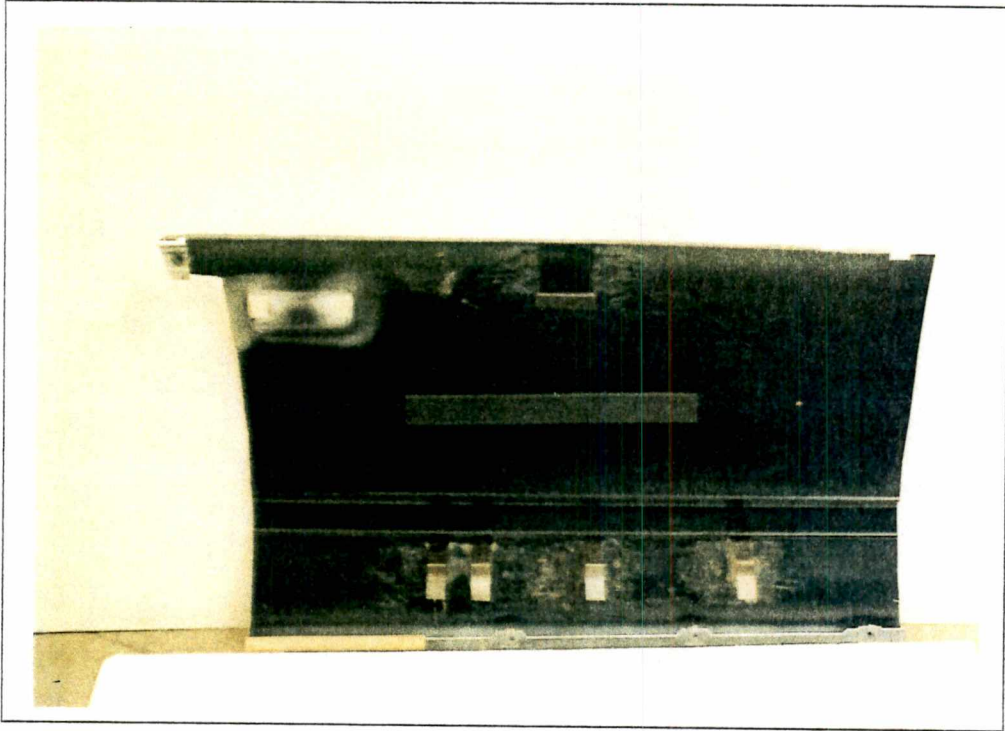


Figure 4.1 - Flexing Design Prototype Panel.

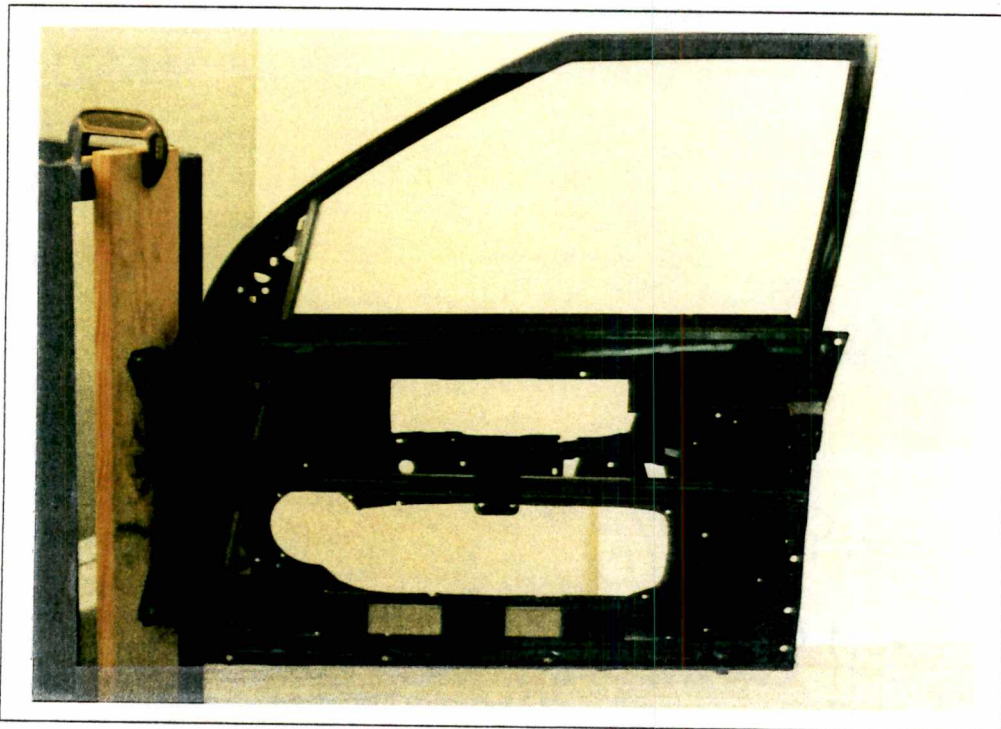


Figure 4.2 - Flexing Design Prototype Frame.

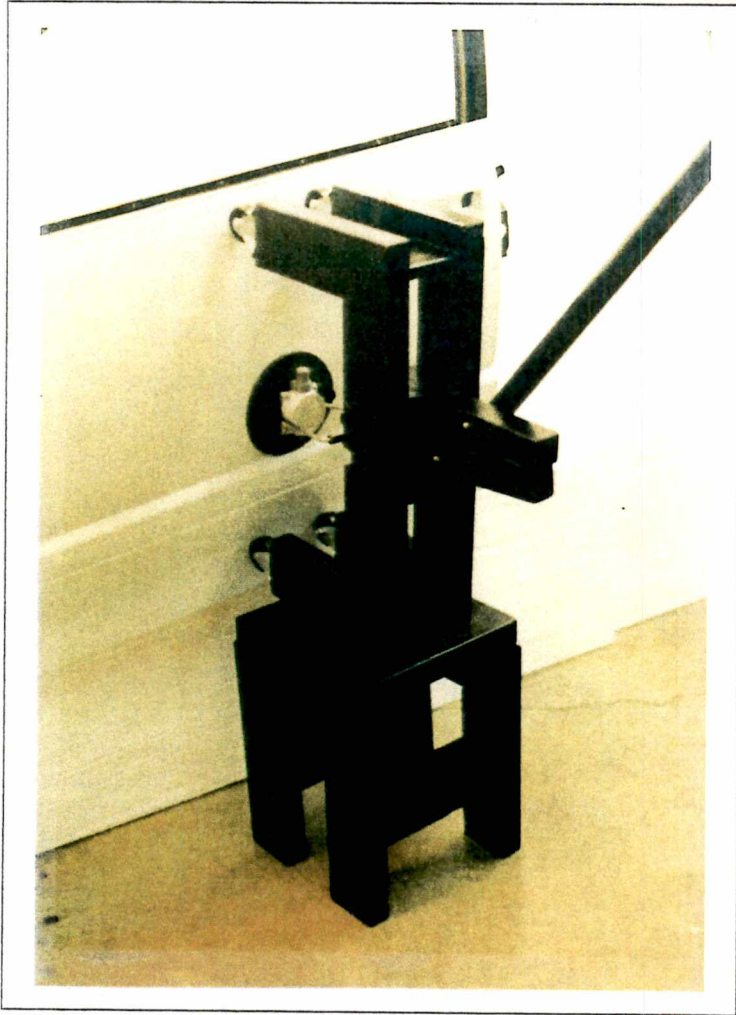


Figure 4.3 - Flexing Device.

in. diameter wheels supplied the bearing surface for the pushing force. The forces are diagrammed in the top of figure 3.4 in the conceptual design chapter. The wheels were intended to protect the painted surface during deflection. For testing purposes two soft rubber wheels and two harder plastic wheels were used to see how the paint would wear.

Three "lower brackets" were spot welded to the bottom of the frame. These brackets were fabricated from 1/16 in. thick steel sheeting and the top edges were bent 180° with a .125 in. radius to create a rounded bearing surface for the lower clips.

Complete shop drawings for all brackets and clips are in Appendix C. An existing sheet metal edge on the frame was used as the top bracket. Two large sections of the interior sheet metal wall were removed to allow access to the inside of the door for prototype construction and for demonstration viewing. These were the only modifications to the frame.

The panel was modified by sawing off the left and right flanges, and attaching the upper and lower clips. The flanges were removed because they acted as stiffeners and prevented panel flexing. Both the upper and lower clips were fabricated from 0.0375 in. thick sheet steel. In mass production, these clips could be inserted into the mold and actually molded into the plastic panel. The prototype clips were attached to the panel by adhesive, fiberglass and polyester resin. Two fasteners, used for securing the panel, were placed in the upper-rear and lower-front corners of the door. No fasteners were used in the middle because the flanges where the n-clips attach were removed. A production design will require two additional fasteners in the middle of the panel.

Prototype clip design

The most difficult design task on this project was to find an upper and lower clip geometry that allows insertion while the panel is flexed and tight clamping once the panel is relaxed. To determine the upper and lower clip geometry, a crude prototype was constructed with wire and attached to a door panel that was flexed over the frame. Also, several thin metal clips were modeled, but these rough prototypes were awkward and did not lead to a solid design.

Computer Aided Drawing (CAD) was an essential design tool used to solve the geometry problem. After constructing the final prototype of the flexing device, a panel was placed against a vertical fixture with tick marks drawn every inch. The panel profile

was sampled every inch with a set of dial calipers and the coordinates were typed into IBMCAD as points. Next, lines were drawn to connect the points. Both the flexed and unflexed panel profiles were recorded in this manner. For verification, the panel profiles were plotted full scale and compared to the flexed and unflexed panels. The sketches did not deviate from the actual profiles by more than 1/4 in. at any point and the clip locations were almost exact. With accurate profiles of flexed and unflexed panels sketched, the location of the frame constraints and brackets were overlaid in the CAD drawing. Then, size and shape of each clip were sketched and fit on the computer model--saving time and money by avoiding costly prototyping mistakes.

The flexing profiles along with clips and brackets are shown in figure 4.4. The left sketch is the flexed profile and the drawing on the right is the normal or relaxed profile. The dotted line indicates an attachment to the door frame--both the lower and upper brackets are part of the door frame. In the flexed profile at the circled numbers 1 and 2, the clips are free to be inserted inside the brackets. Then when the panel is relaxed to its normal position (circled numbers 3 and 4), both clips are in contact with the brackets; thus, holding the panel against the frame.

Assembly Testing

The final flexing prototype of the door panel was tested for ease of assembly by installing the door panel, including the two screw/n-clip fasteners, repeatedly and comparing assembly times with the current Saturn design. Each design was assembled and timed ten times. The results and a complete statistical breakdown of these tests are given in Appendix E. The following is a list of the assembly steps performed in the current design and flexing design assembly time tests.

Flexing Profiles

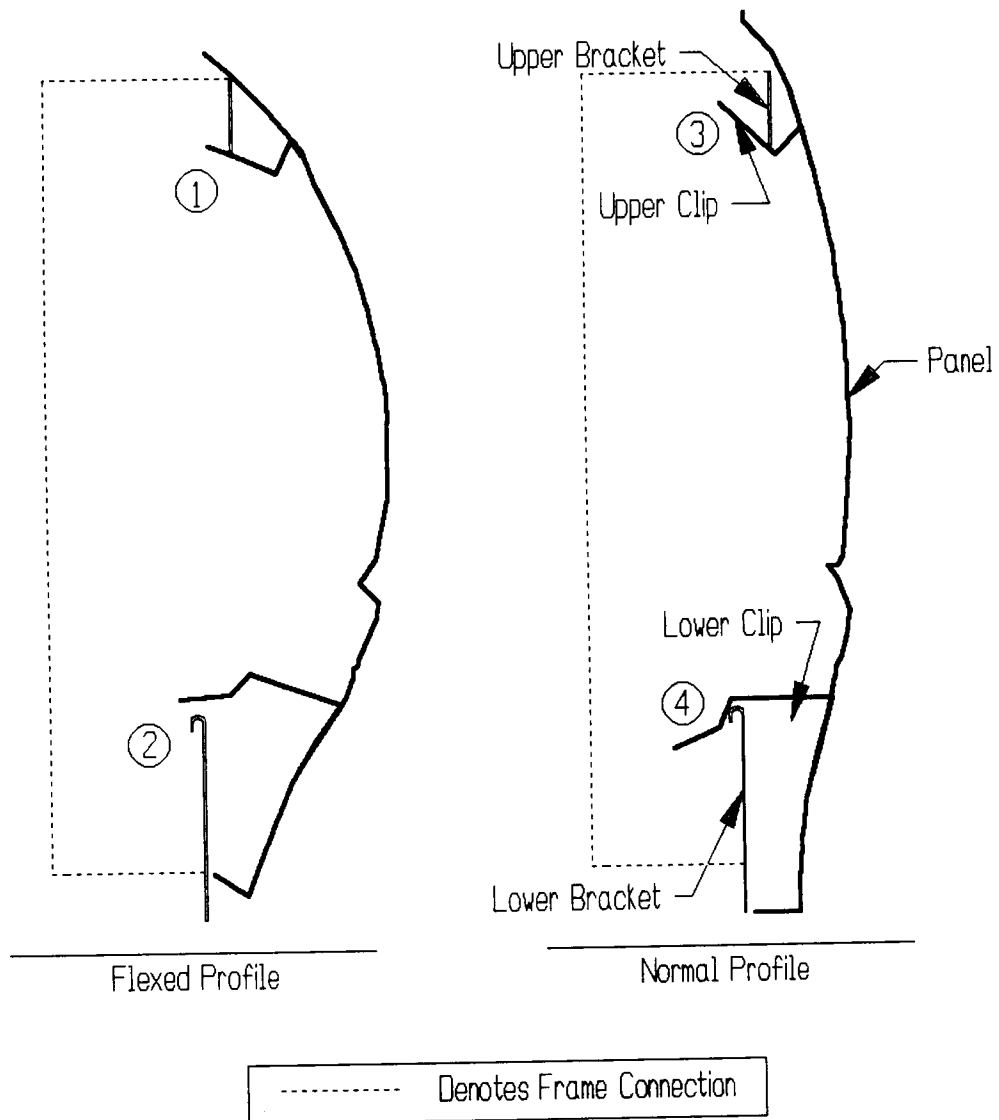


Figure 4.4 - Flexing Profiles

Flexing Design Assembly Steps for Time Testing

1. Insert two (2) n-clips over the holes in the door panel.
2. Flex panel (suction cup already attached).
3. Align panel with frame and relax (unflex) panel.
4. Adjust panel and drive screws into n-clips with a cordless drill/screwdriver.

Current Saturn Design Assembly Steps for time testing

1. Insert nine (9) n-clips over the holes in the door panel.
2. Align panel with frame and clamp together at top.
3. Drive screws into n-clips with a cordless drill/screwdriver and remove clamps.

The results of these time tests are shown in Table 4.1. The flexing design prototype saved an average of 84.9 seconds in assembly time over the current process. The standard deviation of the flexing design was higher than that of the current design because of alignment difficulties on several of the test runs. Some of the above-mentioned alignment problems were due to the crudeness of the prototype. Still, even the slowest sliding assembly time (65 seconds) was 71 seconds faster than the best current assembly time (136 seconds). Furthermore, with a well-made prototype or a precisely injection-molded production door panel, the assembly time could be consistently between 49 and 55 seconds as was the case when the panel aligned well during testing. However, the additional fasteners required in the middle of the panel will add almost 10 seconds to the production assembly time. The projected production assembly time is 62 seconds.

Table 4.1 - Flexing Assembly Time Testing Statistics		
	Assembly Time (seconds)	
Statistic	Current Design	Flexing Design
Mean	142.7	57.8
Median	142.5	57
Standard Deviation	3.9	6.05
Minimum Value	136	49
Maximum Value	149	66
Range	13	17

Paint Testing

The paint on the door panel held up well when it was flexed. Two panels were flexed over 100 times each with no visible signs of chipping, cracking, or peeling. As mentioned in the prototype description, two different sets of wheels were used on the flexing device—one set of soft rubber casters and one set of hard plastic casters (to see how much punishment the paint could take). The rubber wheels did not mar the paint at all; however, the hard plastic wheels made permanent visible black lines when the panel was deflected. If Saturn opts to implement this design, a soft rubber wheel is recommended for any type of flexing device.

General Observations

The sheet-metal lower clips were designed with ergonomics in mind. They have a severe change in slope at the point of attachment so that as the panel is relaxed and the clips mate with the brackets, the installer feels the panel "pop" into place. This perception is very important in this design because it tells the worker that the panel is in place and fully relaxed. If the workers are using an automated flexing device he/she may not realize that the panel is in place. Prototype testing indicated that the "pop" was quite noticeable.

Unfortunately, the flexing prototype did not hold the door against the frame as well as the current design or the sliding prototype. At the bottom edge where four clips were intended to fix the panel to the frame securely, the panel could be pried loose with less than 10 lbs. of pressure at the rear end. While the prototype is far from an acceptable design, it does provide an accurate model for assembly testing.

Conclusions and Recommendations

Development and implementation of the flexing design will be difficult for several reasons. First of all, a solid attachment of the panel to the frame is a necessity, and, has not yet been attained. Second, if the metal clip approach is applied, the convoluted door mold will become even more complicated. Furthermore, this design will require a special tool, a flexing device, at every Saturn dealer and body shop, and a large, possibly ceiling mounted, mechanical/pneumatic flexing device at the assembly plant in Spring Hill, Tennessee. Also, all stiffeners such as the flanges must be eliminated for the panel to flex which will alter the appearance of the doors. Lastly, the sliding prototype has a faster assembly time and is a simpler design.

The flexing design does show promise, and, if properly developed, could prove to be the best attachment method. The assembly time was significantly lower than that of the current design. Also, if the flexing design is technically feasible, it will require only a minimal amount of physical labor to install because a mechanical/pneumatic flexing device can be developed to flex and hold the door panel during installation. Both the current design and the sliding design call for significantly more physical effort during installation. Another positive feature of the flexing design is that it reduces the number of fasteners. If metal clips such as the ones used in the prototype are developed, the creep and stress relaxation problems discovered in the sliding design will be a non-issue.

This design should be pursued from a "clean sheet" perspective. Saturn should not attempt to fit this design to their existing door panel and frame.

Chapter 5

Sliding Design

Design Description

Theory of Operation

As mentioned in the brief description of the sliding concept in chapter 3, the sliding design consists of a series of hooks that are intended to be injection molded into the back of the door panel. An isometric sketch of a "slide hook" is shown in Figure 3.5 and the sliding mechanism used to clamp the door panel to the frame is illustrated in Figure 3.6. To attach a panel, the hooks are aligned with slots in the door frame. Each slot has a small tab bent at the base of the slot perpendicular to the door. The hooks are inserted in the slots and pushed downward over the tab. As the hook moves downward, the tab, which is slightly longer than the gap in the hook, pushes the hook outward. The hook then acts as a deflected cantilever beam that produces a clamping force holding the panel against the frame. The clamping force is a function of the amount of deflection and the stiffness of the cantilever beam.

Slide Hook Features and Geometry

A cross section of the final design that was prototyped and tested is shown in Figure 5.1. Since the slide hook is intended to clamp the panel to the frame and is not meant to locate the panel (the two fasteners provide location), the hook must provide sufficient clamping force to impede vibration and preclude looseness, and still permit the door panel to be adjusted for alignment with neighboring body panels. In other words,

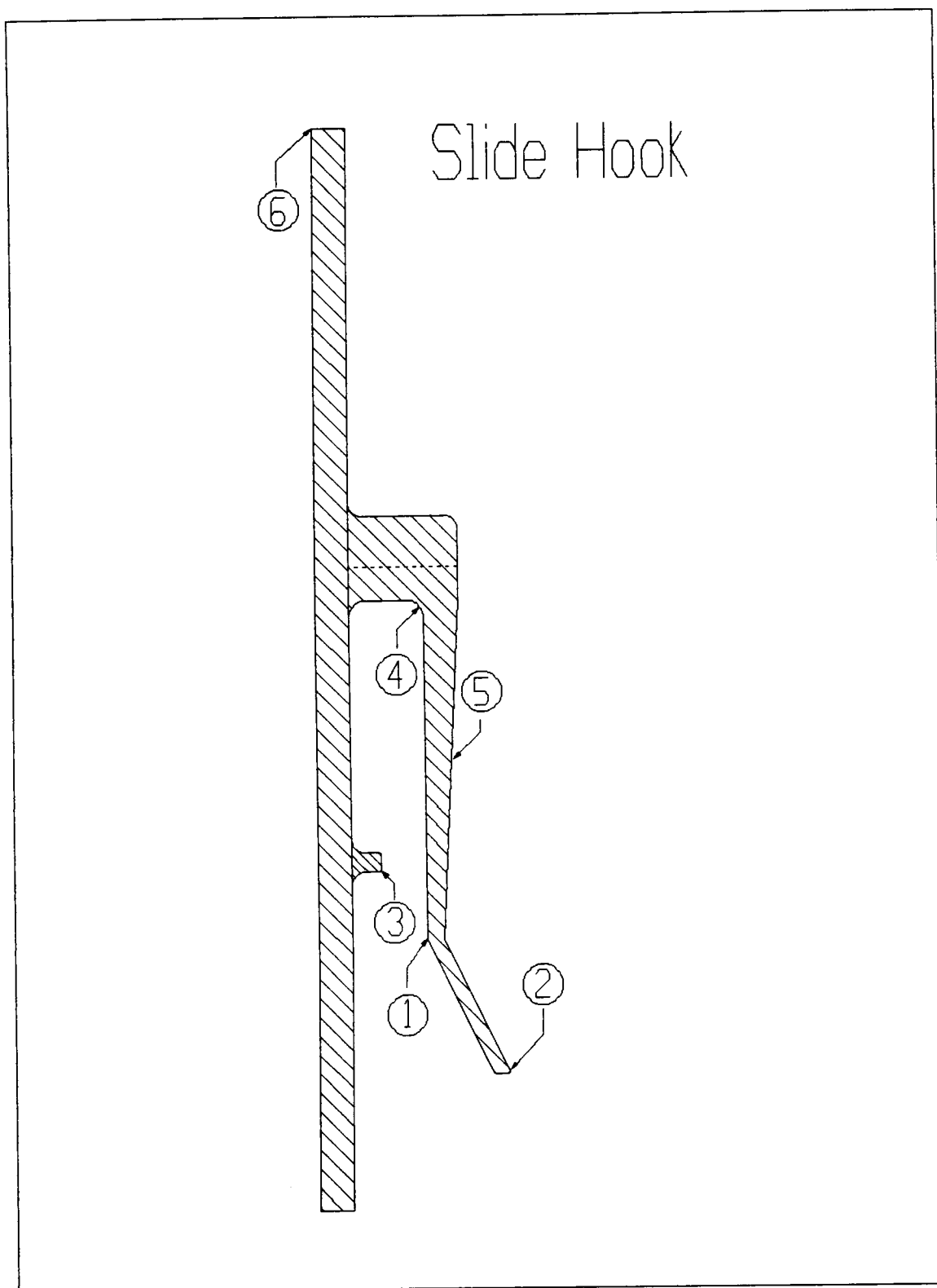


Figure 5.1 - Slide Hook Cross Section.

the slide hook must be able to move both vertically and horizontally over a given distance without loosening or breaking. Position "1" on Figure 5.1 is the point at which the slide hook is first fully deflected--it is 1.25 in. from the base of the cantilever, position "4." Position "3" is a stop that limits the distance that the hook can slide--it is 1.0 in. from position "4." Clamping force must be sufficient to impede vibration at any point within the 1/4 in. vertical travel from position "1" to position "3". For horizontal positioning, the width of the hook is 1/2 in. smaller than the mating slot in the door frame allowing a line worker to align the door freely before inserting two fasteners for final location.

Another feature of the slide hook is the "guide" shown by the number "2" in Figure 5.1. This angled extension's sole purpose is to aid in the insertion of the hook into the slot. Position "5" in Figure 5.1 shows the tapered edge that provides the necessary flexibility in the cantilever beam while supplying a relatively large cross section in the high stress area at the base--position "4". The taper design is discussed in detail in the "cantilever taper optimization" section of this chapter.

The slide hook is designed to be injection molded. Injection molding requires special considerations such as wall thickness of parts and draft angle. The complete drawings for the hook are in Appendix C. As noted on the drawings, all vertical mold surfaces should be tapered 1° for draft angle to allow for unconstrained removal of the door panel from the mold. Furthermore, the typical working range of nominal wall thickness for injection molded ABS is 0.045 in. - 0.140 in. [Hoechst, 1989]. If the wall thickness is less than 0.045 in., it may compromise structural integrity. If the wall thickness is greater than 0.140 in., the surface may have unattractive indentations or impressions. All slide hook wall thicknesses are within the recommended range.

Operating Space

The operating space for the sliding design is dictated by the minimum and maximum amount of clamping force provided by the slide hooks. The lower limit of the operating space is defined by the minimum allowable clamping force, that is the smallest amount of clamping force needed to impede vibration of the panel against the door frame. The minimum clamping force is 0.75 lbs. per hook. The deflection of the hook is 0.065 in. + .025, - .036. The deflection tolerance is derived from the tolerance of the injection molded hook and the tolerance of the stamped tab. "In most cases the commercial tolerances of 0.005 in. can be maintained" in injection molded parts [Deale, 1970]. The stamped tab requires a tolerance of +/- 0.02 in. and a bend tolerance of +/- 2° [Xerox, 1988]. The upper limit of the operating space is governed by the maximum allowable stress in the slide hook. For the ABS/PC polyalloy material in the door, the yield strength is approximately 8000 psi, so the slide hooks maximum allowable stress is 4000 psi using a safety factor of two. Theoretically, with the sliding design geometry, a clamping force of 5.72 lbs. per clip can be obtained without violating the maximum allowable stress. Therefore, the upper limit of the operating space is 5.72 lbs. per hook.

Cantilever Taper Optimization

Tapering the cantilever beam section of the hook, surface "5" in Figure 5.1, was necessary to allow the 1/4 in. vertical travel between position "1" and position "3" and, at the same time, maintain the clamping force in the specified operating space. A constant cross-section beam does not provide enough flexibility to stay within the upper limit of the operating space; that is, the stress at the base exceeds 4000 psi with a constant cross-section beam. The taper was optimized with a "transfer matrix" program written in Quick basic and listed in Appendix D. The program calculates clamping force and

maximum stress for a given deflection at specified locations between positions "1" and "3" on the beam. Clamping forces and maximum stresses were checked for three deflections--the nominal deflection of 0.0649 in., the maximum deflection of 0.0899 in., and the minimum deflection of 0.0249 in. The numerical results of these calculations are listed in Appendix D.

The "transfer matrix" program results are plotted in Figure 5.2 and Figure 5.3. Figure 5.2 is a plot of the clamping force versus the deflection location between positions "1" and "3" (Figure 5.1), where position "3" is 1.0 in. from the base of the cantilever beam and position "1" is 1.25 in. from the base of the cantilever beam. The maximum clamping force is 5.72 lbs. for a deflection of 0.0899 in. at a position 1.25 in. from the base of the cantilever. The minimum clamping force is 0.89 lbs. for a deflection of 0.0294 in. at a position 1.25 in. from the cantilever base. Figure 5.3 is a plot of the maximum stress versus the deflection location between positions "1" and "3." The highest stress is 4000 psi for a deflection of 0.0899 in. at a position 1.0 in. from the base of the cantilever. The lowest stress is 778 psi for a deflection of 0.0294 in. at a position 1.25 in. from the cantilever base.

Prototype Testing Results and Observations

Prototype Description

A prototype of the sliding design was fabricated by attaching five hooks to the back of a modified drivers-side SL2 door panel. The hooks were milled from a block of unfilled (natural) ABS. They were then fiberglassed onto the back of the door panel. As mentioned in the previous section, each hook slides into a corresponding slot in the door frame. Two of these slots were milled in the door frame and three additional slotted

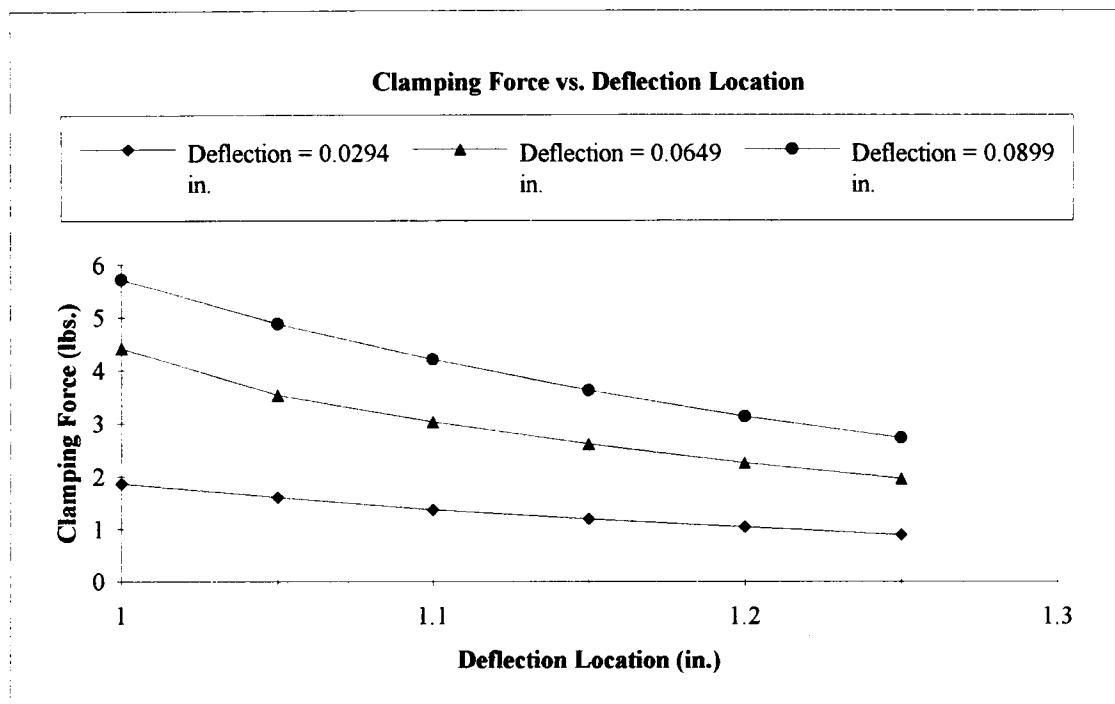


Figure 5.2 - Clamping Force Curves

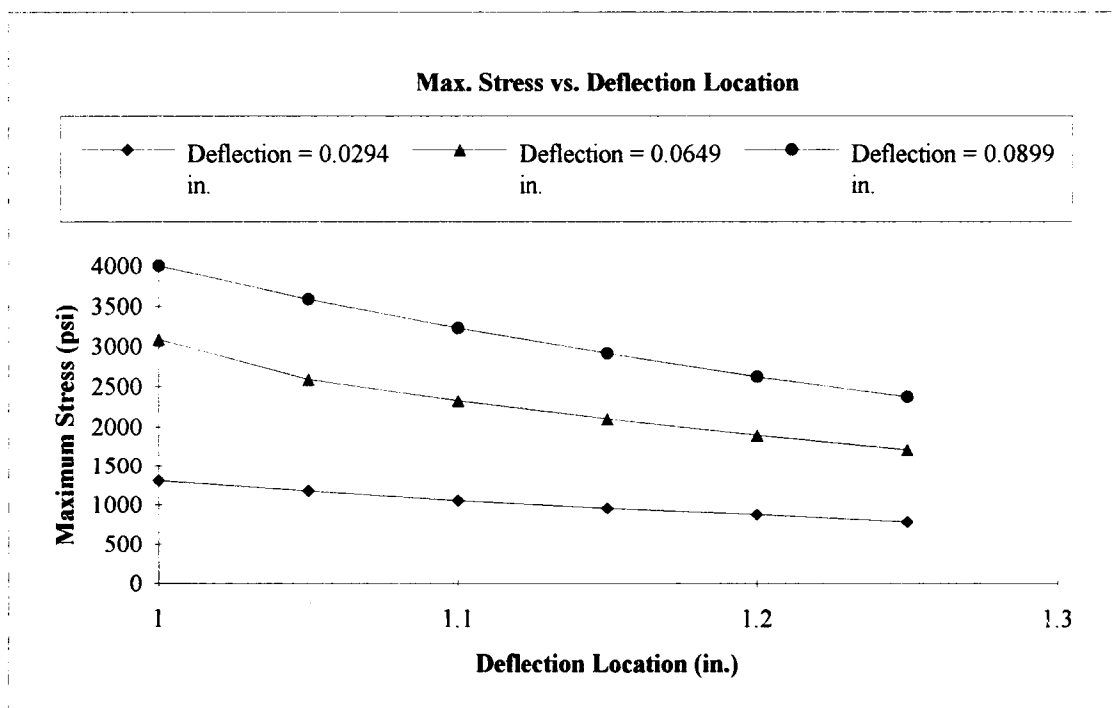


Figure 5.3 - Maximum Stress Curves

plates were spot welded to the frame. Fiber glassing was necessary to "build up" the surface of each hook so that the hooks mated with the slots in the door frame. A production sliding door would require ribs or flanges in lieu of the fiber glass "build up". All told, the hooks were in three different planes--the two slots in the frame were in different planes and the three plates were in the same plane, yet different from the two frame slots. In addition to the hooks, two of the n-clip/screw fasteners were used to locate and secure the panel after alignment. Figure 5.4 is a photograph of the sliding prototype panel. Figure 5.5 is a photograph of the sliding frame with five slots. Some modifications to both the panel and frame were necessary for prototyping. The most significant panel modification was the partial removal of the upper-rear flange. The flange wraps around three sides of the door and provides the holes used for the n-clip/screw fasteners. The section that was removed interfered with a section of the frame and curtailed the desired sliding motion. This section not only interferes with sliding, but makes the current assembly process more difficult because the panel must be hooked around the upper rear flange. Removing the section of flange does not affect the appearance of the door in any way and does not adversely affect the sliding prototype because the flange is not used in this area of the panel. Besides cutting the slots and welding the slotted plates in the door frame, only two modifications were necessary. The door latch was removed from the frame because it protruded through the panel and interfered with the downward sliding motion required in this design. It would be possible to slide the door up over the latch, but fighting gravity in this design would be counter productive from a human factors/ergonomic perspective. A new modular door handle design is being developed by Saturn for future cars that may eliminate the sliding interference [Longard, 1993]. If the new door handle does not provide the needed clearance, it may be possible to develop a handle which attaches after the door panel is

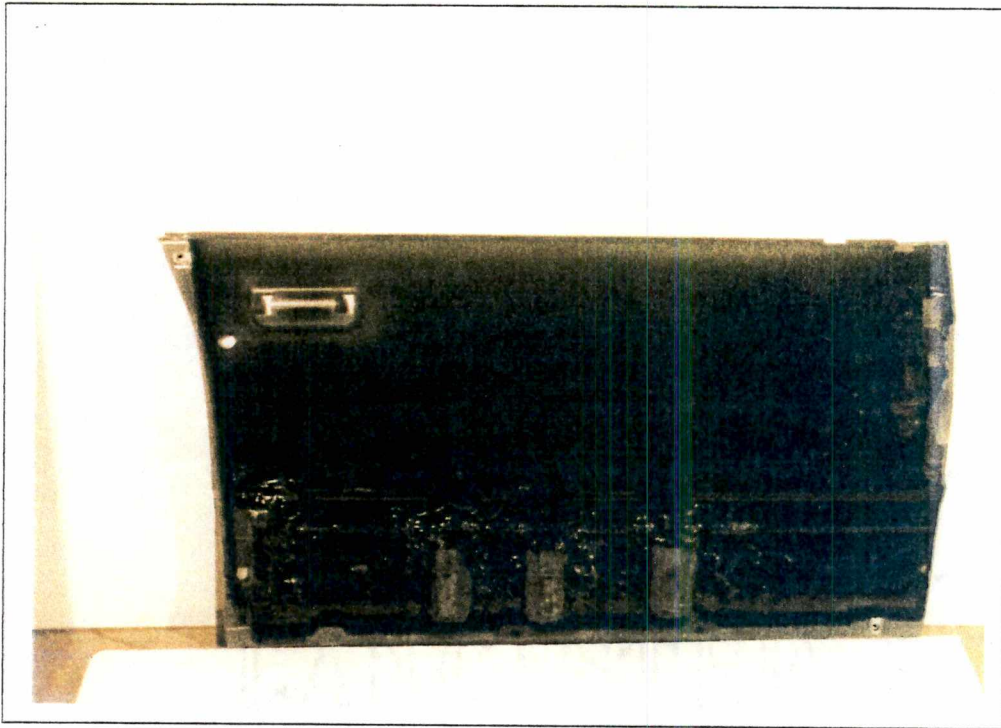


Figure 5.4 - Sliding Design Prototype Door Panel

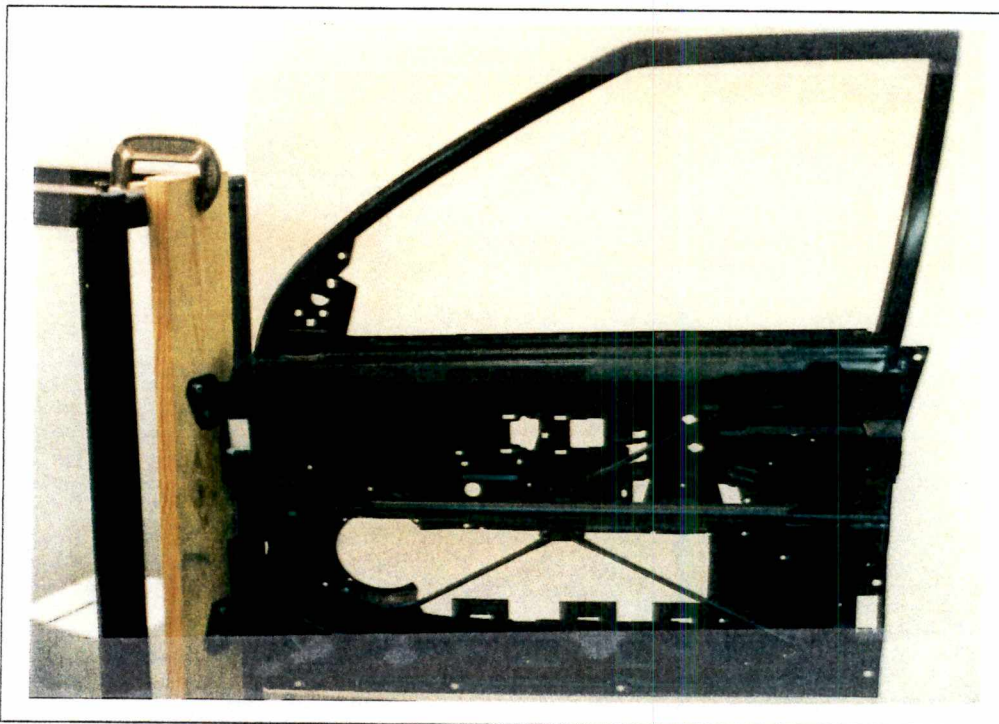


Figure 5.5 - Sliding Design Prototype Door Frame

in place. The other major modification to the door frame was the removal of two structural cross bars which attached to the main steel bar and ran diagonally down to the bottom of the door. These bars interfered slightly with alignment of the hooks to the slots; however, the prototype panel can be attached with the bars in place with only small assembly time penalty. The only other modification of note to the door frame was the removal of the lower interior metal wall. This was done for demonstration and viewing purposes only and does not affect function. It should be noted that the door frames used for prototypes did not contain any latch or window mechanisms or the window glass.

Material Differences

Due to the prohibitive cost and complexity of making a mold and injection molding the ABS/PC door panel resin at the proper temperatures and pressures, the slide hooks were milled out of the closest available material, unmodified ABS. The ABS properties compare favorably to the ABS/PC polyalloy used in the door. The one difference of significance is Flexural Modulus. The ABS/PC blend has a Flexural Modulus of 420,000 psi [Skornicka, 1993] while the prototype ABS has a Flexural Modulus of approximately 350,000 psi, 20% less. This means that the actual injection molded hooks made of the ABS/PC polyalloy will be approximately 20% stiffer. The slide hook was designed for the ABS/PC material so the prototype is "flimsier" than the optimum design. The other mechanical properties differ slightly, but none of the differences are significant to the design of the slide hook.

Creep and Stress Relaxation

As with any plastic part in tension, the slide hooks are subject to stress relaxation or creep. In general, creep and stress relaxation testing is performed on specimens with tensile, compressive or flexural loads or deformations [Charier, 1990]. Creep and stress relaxation testing of individual parts is unusual. In fact, Saturn does not normally test individual parts for creep or stress relaxation [Quinlan, 1993]. In a typical creep test, the specimen is subjected to a constant load (and constant stress) and the corresponding strain is measured periodically for a given duration. A stress relaxation test is the opposite of a creep test. Here a specimen is deformed (strained) a given amount and the diminishing stresses are recorded as a function of time.

Four relaxation tests were performed on the prototype slide hooks. Three of these tests were short term tests at elevated temperatures between 130° Fahrenheit and 180° Fahrenheit. A long-term test was performed on a slide hook at room temperature for 30 days.

The room temperature relaxation test was performed on one prototype hook. The hook was placed in a slotted plate identical to the ones that were spot welded onto the frame. Then, the hook was stressed as intended in the design with the maximum force, approximately 5.7 lbs, creating a flexural stress of roughly 4000 psi. Once a day for 30 days the hook was removed from the slotted plate and the distance from the rectangular base to the end of the taper (on surface "5" directly above position "1" in Figure 5.1) was recorded. This test was performed at room temperature--68° to 72° Fahrenheit. The results of this test are plotted in Figure 5.6.

As expected, the material "distorted" at a high rate initially before tapering off toward the end of the measuring period. The end of the hook distorted a total of 0.016 in. from 0.382 in. to 0.398 in. This test was performed under the maximum stress of

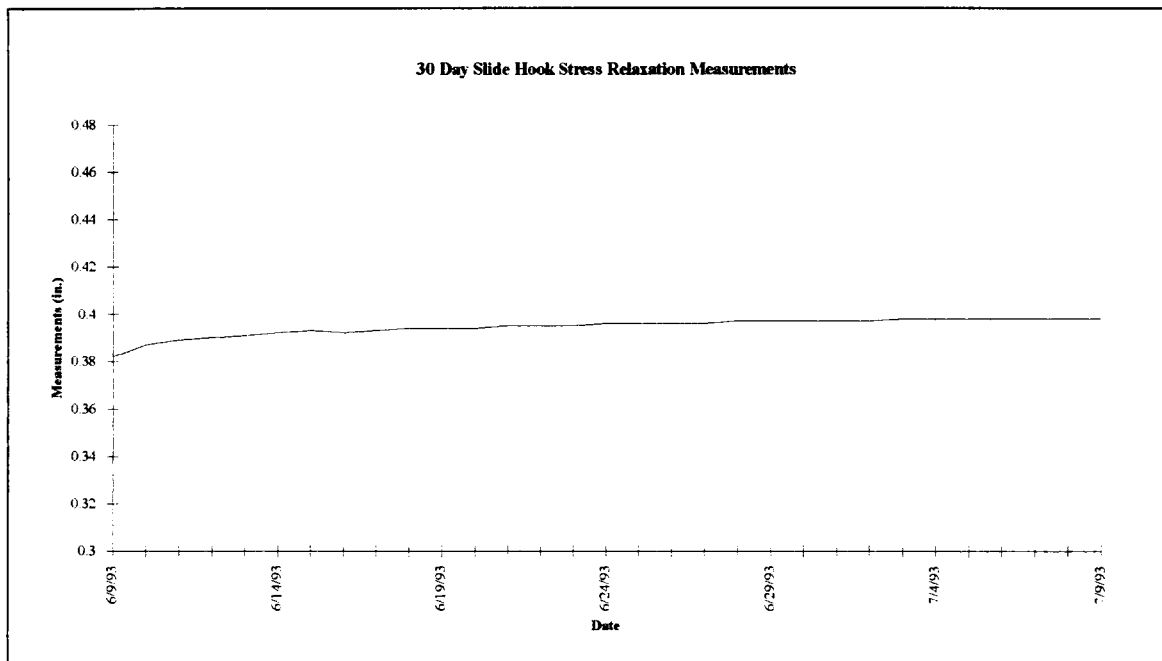


Figure 5.6 - Creep/Relaxation Results

approximately 4000 psi so the cantilever deflection was about 0.0899 in. If the distortion is subtracted, the corrected deflection is still 0.0739 in. which is 0.009 in. above the nominal deflection and 0.0445 in. above the minimum allowable deflection--well within the hook's operating space. Regrettably, no clamping force measurements were taken during the 30 day test; however, the 48 hour elevated temperature test indicates that a highly linear relationship exists between relaxed cantilever deflection and clamping force. This relationship is described below.

The elevated temperature testing was not as promising. The procedure for this test was as follows. A prototype slide hook was placed in a slotted plate as outlined in the room temperature testing description. It was then placed in a convection testing oven set at the prescribed temperature. Periodically, the sample was removed and the deflection and clamping force were measured. The permanent deflection was measured

with a dial indicator in the same manner as the room temperature measurements. The clamping force was ascertained by pulling on the cantilever beam with a spring scale.

The hook failed within five hours at 180° Fahrenheit. It had almost completely relaxed to the deflected position. The clamping force was measured at less than 0.5 lb. which is less than the 0.75 lb. minimum allowable force.

At 150° Fahrenheit the slide hook did not fail within the 24 hour test duration; however, the clamping force dropped from 4.25 lbs. to 1.25 lbs and showed no signs of stopping. It appeared that the hook would fail within one week at 150° Fahrenheit.

The last elevated temperature test was performed at 130° Fahrenheit for 48 hours. The hook did not fail during this test and the relaxation slowed to an acceptable level. The results of the 48 hour test are plotted in Figures 5.7 and 5.8. The final clamping force recording was 2.4 lbs.--well above the failure force of 0.75 lbs. Also, the Measured deflection of the slide hook followed the rate of force relaxation (the slopes of Figure 5.7 and 5.8 were almost mirror images of each other). This indicates that the clamping force and permanent deflection have an almost linear relationship.

These simple tests show that stress relaxation is a significant problem at elevated temperatures. They also show that at room temperature, the majority of the first month's distortion occurs within two weeks of the assembly. However, comprehensive testing must be performed on the ABS/PC door material (the tested prototype was machined from a block of unmodified ABS) before any conclusions can be drawn about the effects of creep and stress relaxation. This testing is strongly recommended if Saturn engineers decide to further investigate this design.

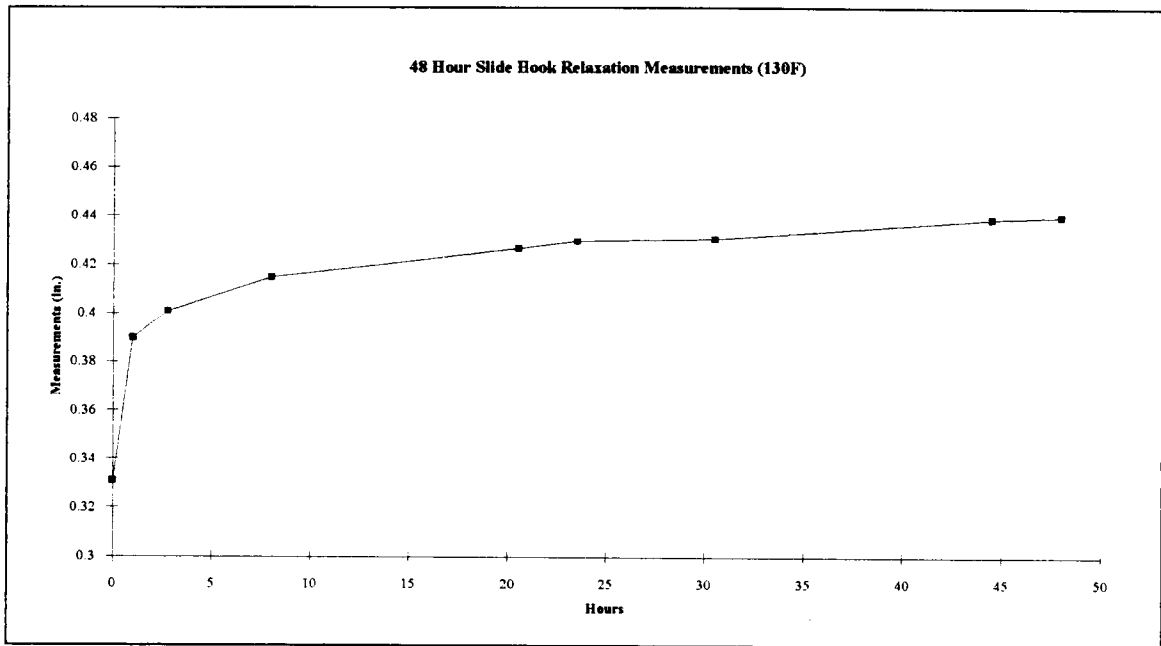


Figure 5.7 - Measurement Relaxation Results (130° F).

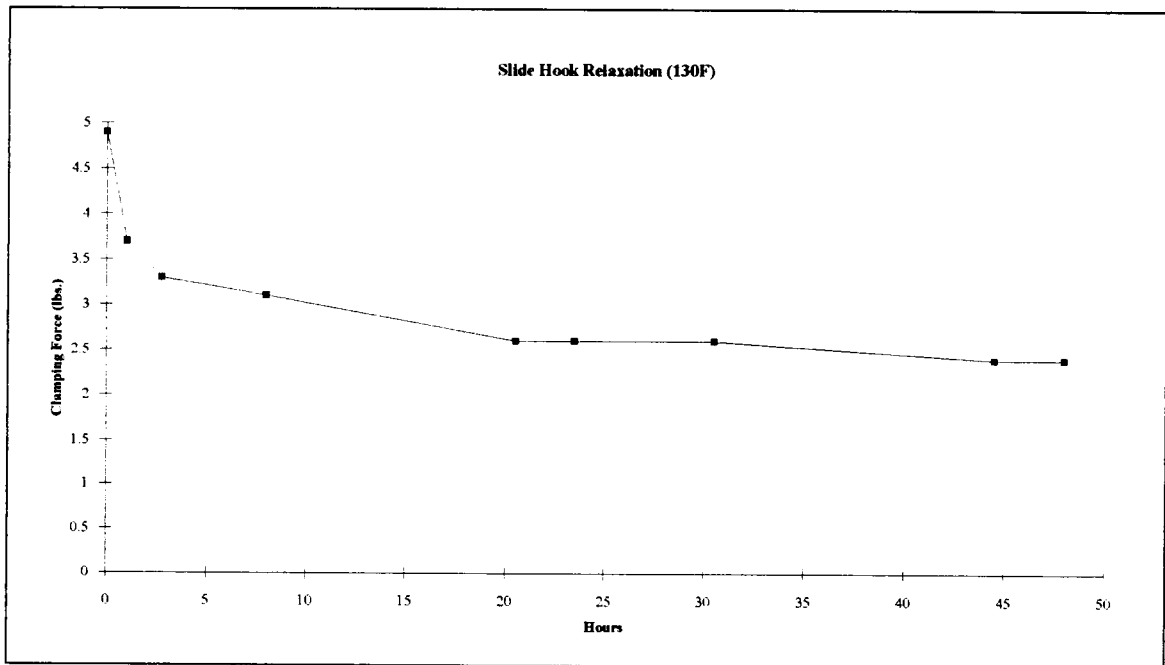


Figure 5.8 - Clamping Force Relaxation Results (130° F)

The slide hook was designed to provide acceptable clamping forces at stresses above 800 psi. It was thought that the ABS would not creep below that limiting stress. Unfortunately, at elevated temperatures the slide hooks do creep below 800 psi. If the ABS/PC door material fails to withstand the elevated temperatures, alternate materials from high temperature plastics to metals should be considered, and, if necessary, used as mold inserts.

Plastic Shaving

As the plastic hook slides over the sheet metal tab as shown in Figure 3.5, the sharp edge of the sheet metal shaves a small amount of plastic from the contact surface. If too much material is shaved from the inside of the slide hook, it could reduce the amount of clamping force below the lower limit of the specified operating space. One prototype clip was tested for shaving by slipping it on and off the slotted plate over 100 times. The maximum amount shaving was 0.008 in. which should not significantly lower the clamping force. If shaving caused problems, it could be partially corrected by breaking the sharp edges of the sheet metal tab at a 30° angle. Still, it is unlikely that a door will be removed more than 100 times for service during its life. Also, the ABS/PC material may not be as prone to shaving as the unmodified ABS used in the prototype because the ABS/PC blend has superior mechanical properties--strength, stiffness, and impact resistance.

Assembly Testing

The final prototype of the door panel was tested for ease of assembly by installing the door panel, including the two screw/n-clip fasteners, repeatedly and comparing assembly times with the current Saturn design. Each design was assembled and timed

ten times. The results and a complete statistical breakdown of these tests are given in Appendix E. The following is a list of the assembly steps performed in the current design and sliding design panel attachment time tests.

Sliding Design Assembly Steps for Time Testing

1. Insert two (2) n-clips over the holes in the door panel.
2. Align panel with frame, insert hooks in slots and slide down over tabs.
3. Drive screws into n-clips with a cordless drill/screwdriver.

Current Saturn Design Assembly Steps for time testing

1. Insert nine (9) n-clips over the holes in the door panel.
2. Align panel with frame and clamp together at top.
3. Drive screws into n-clips with a cordless drill/screwdriver.

The results of these time tests are shown in Table 5.1. The sliding design prototype saved an average of 96.5 seconds in assembly time over the current process. The standard deviation of the sliding design was higher than that of the current design because of alignment difficulties on several of the test runs. Some of the above-mentioned alignment problems were due to the crudeness of the prototype and the fact that the fibreglassed slide hooks were not perfectly located. Still, even the slowest sliding assembly time (55 seconds) was 81 seconds faster than the best current assembly time (136 seconds). Furthermore, with a well-made prototype or a precisely injection-molded production door panel, the assembly time could consistently be between 36 and 45 seconds as was the case when the panel aligned well during testing.

Table 5.1 - Assembly Time Testing Statistics		
	Assembly Time (seconds)	
Statistic	Current Design	Sliding Design
Mean	142.7	46.2
Median	142.5	46.5
Standard Deviation	3.9	5.51
Minimum Value	136	36
Maximum Value	149	55
Range	13	19

Slide Hook Force Testing

Two types force tests were performed on prototype slide hooks identical to the hooks used on the prototype door--one test to determine the strength of a hook at failure and one test to verify the clamping force. The first test was a destructive test where a hook was placed in a slotted test plate. The plate was clamped to a vice and the slide hook was pulled with a spring scale until the part failed. This test was performed on only one sample because it was a destructive test.

The slide hook failed with a 17 lb. load at the end of the taper. As expected, failure occurred at the base of the cantilever beam. The plastic made a "popping" sound and small cracks began to propagate around the base of the cantilever section. The 17 lb. load exceeds the predicted breaking value of 10.4 lbs. by 63.5%; however, the 10.4 lbs. predicted value was a conservative estimate. Of course, if the slide hooks can consistently withstand 17 lb. loads before failure, the door attachment will be even stronger than expected.

The second set of tests concerned clamping force verification and was performed on three slide hook specimens. Each slide hook was placed on a slotted plate in a vise and the maximum and minimum clamping forces were measured with a spring scale. The tapered beam portion of the hook was pulled with the spring scale at the end of the

taper for the minimum clamping force measurement, and at the stop position, 1 in. from the base of the cantilever beam, for the maximum clamping force measurement. The results of these tests are given in table 5.2. All clamping force measurements were within the prescribed operating space, that is, between 0.75 lb. and 5.72 lbs.

Table 5.2 - Clamping Force Test Results		
	Clamping Force (lbs.)	
Specimen #	Minimum	Maximum
1	2.75	4.8
2	2.5	5.25
3	3	5.6

Conclusions and Recommendations

The sliding design is a viable alternative to the current method of attaching Saturn door panels. Changing to the sliding design will save money and reduce assembly time. Results of prototype testing show that it is a technically feasible design that provides a solid attachment and maintains the current appearance of the car; that is, the outside of the door panel is not cosmetically altered. The only potential flaw in the sliding design is stress relaxation. If the ABS/PC material cannot withstand elevated temperatures, as was found with the unmodified ABS, then other materials must be explored. The solution may be to use metal or high temperature plastic slide hooks and insert them into the mold during the manufacturing process.

The drawback to the sliding design is that it requires a complex mold with slides to produce the gap in the slide hooks. However, the current door design requires at least three large slides to mold the three flanges on the sides and bottom of the door for the screw/j-clip fasteners. The bulk of these flanges can be eliminated in the sliding design mold because it only requires two fasteners instead of nine. Consequently, while the

sliding design mold will be complicated, it is not eminently more difficult to tool than the current mold. And since the molds must be retooled each time the architecture of the door changes, switching to the sliding design will be expensive, but not out of line with normal retooling costs.

Design Development Recommendations

Like most new products, the sliding design shown will require a significant development effort. The slide hook drawings in Appendix C provide a good foundation for the development of a sliding method of attachment. From a clamping force standpoint, the slide hooks met all requirements in the tests described in the previous section except for creep; however, it is strongly recommended that Saturn perform extensive force testing on the hooks. This level of testing was beyond the scope and resources required for this project. The creep/stress relaxation failures must be overcome by alternate material selection.

During assembly testing insertion of the hook through the slot proved difficult. The hook cleared the edges of the slot in the horizontal direction, but the slot was not large enough in the vertical direction. The prototyped slots permitted a horizontal clearance of one in. but the vertical clearance was less than 1/4 in. because of limited space on the door frame. A vertical insertion clearance of 3/4 in. to 1 in. is strongly recommended for future designs. Also, rounding off the corners of the angled guide will aid insertion.

Slide Hook Location

The prototype slide hooks were located without a choice due to space considerations. Ideally, the six to eight hooks should be placed as close to the outer edge

of the frame and panel. A good starting point would be to place hooks where fasteners are currently located. This would require seven hooks and the two fasteners. The prototype fastener locations (in the upper left and lower right corners of the door) work well and provide excellent stability.

Cost Savings

If implemented on all door panels, the sliding design could save Saturn over \$800,000 per year in labor costs at current production levels. This cost savings is based on a conservative \$35/hr labor rate and the current production rate of 300,000 vehicles per year. Naturally, the savings will increase if Saturn increases production to meet customer demand--as expected.

The sliding design will also reduce the material cost by eliminating 7 screw/n-clips per door. Each set of screw/n-clips costs approximately 20¢ so the material savings will be approximately \$1,600,000. In summary, a design change from the current process to the sliding design will, conservatively, save a total of approximately \$2,400,000 annually in labor and materials.

BIBLIOGRAPHY

BIBLIOGRAPHY

- Boothroyd, Geoffrey. Assembly Automation and Product Design. New York: Marcel Dekker, Inc., 1992.
- Charrier, Jean-Michel. Polymeric Materials and Processing: Plastics, Elastomers, and Composites. New York: Hanser Publishers, 1991
- Dearle, D. A. Plastic Molding Technique. New York: Chemical Publishing Co., Inc., 1970.
- Dym, Joseph B. Injection Molds and Molding: a Practical Manual. 2nd ed. New York: Van Nostrand Reinhold Company, 1987.+
- Hoechst Celanese Engineering Plastics Division. Designing with Plastics: The Fundamentals. Chatham, NJ: Hoechst, 1989.
- Lincoln, Brayton, Kenneth J. Gomes, and James F. Braden. Mechanical Fastening of Plastics: an Engineering Handbook. New York: Marcel Dekker, Inc., 1984.
- Longard, Kevin. Personal interviews. 6 Jan. and 17 Mar. 1993.
- Mahoney, Larry. Personal interview. 6 Jan. 1993.
- Middendorf, William H. Design of Devices and Systems. New York: Marcel Dekker, Inc., 1990.
- Pugh, Stuart. Total Design: Integrated Methods for Successful Product Engineering. New York: Addison-Wesley, 1990.
- Quinlan, John. Personal interviews. 17 Mar. and 22 Jun. 1993.
- "Resins and Compounds." Modern Plastics: Buyer's Guide & Encyclopedia '93. Hightstown, NJ: McGraw Hill, 1993.
- Roark, Raymond J., and Warren C. Young. Formulas for Stress and Strain. New York: McGraw Hill, 1975.
- Skornicka, Joe. Personal interview. 31 Mar. 1993.

APPENDIXES

APPENDIX A - SPECIFICATIONS

Saturn Door Attachment Project

Product Specifications

• Design Specification

1. Attachment should allow door to grow thermally across mating steel flange.
2. Door and outer panels shall meet gaps and flushness criteria. Per exterior panel sections.
3. Panels should avoid squeak, rattle and wind noises.

• Performance/Quality/Reliability/Durability Specification

1. Finished part shall function within door system with no visible change from as received condition and remain fastened to the structure following:
 - Door durability slamming system validation - FBTP 126 and 127 (70,000 cycles on front door at room temperature).
 - GM R-15-34-82 DPG durability (hot soak durability).
 - GM R-15-52-84 Kapuskasing durability (cold soak durability).
2. Doors shall operate after bumper impact per FMVSS 215.
3. Door panels shall pass gap and flush, after Solar Shake Test (SATURN Test 5008). The swing clearance must be a minimum of 0.5mm door/fender, door/door panel, door/quarter panel.
4. Fastener finish requirement - exposed surface - GM 6138M Black.
5. The door shall successfully complete the following reliability tests:
 - Door structural slam test FBTP 114 to a minimum of 20,000 cycles on the front door with no failures. The door system should demonstrate a MCBF (mean cycle between failure) of 140,000 with 50% confidence minimum, 75% confidence preferred.
 - Door durability slam test FBTP 126 to a minimum of 70,000 cycles on the front door with no failures. The door system should demonstrate a MCBF of 140,000 with 50% confidence minimum, 75% confidence preferred.
6. The door system shall have a useful life of 10 years/100,000 miles at the 95 percentile customer usage.

Serviceability

1. Mechanical fasteners that are common, if possible throughout the entire vehicle, are accessible for service using common hand tools, and are reusable.
2. Fasteners should be accessible for replacement and adjustment.
3. Normal towing of the vehicle should not damage the components.

Manufacturability/Assembly

1. Door outer panels to be designed for ease of assembly to the body.
2. Fasteners should be easily accessible.
3. Use minimum number of fasteners (fastening points) for quick assembly.*
4. Use one piece fasteners or, if possible, eliminate separate mechanical fasteners (i.e. mold fasteners into door panel).*

Critical Specifications

1. Fasteners should be accessible for assembly, replacement and adjustment.
2. Use minimum number of fasteners (fastening points) for quick assembly.*
3. Use one piece fasteners or, if possible, eliminate separate mechanical fasteners (i.e. mold fasteners into door panel).*
4. Mechanical fasteners that are common, if possible throughout the entire vehicle, are accessible for service using common hand tools, and are reusable.
5. Attachment should allow door to grow thermally across mating steel flange.

* Denotes new specification not original SATURN specification.

APPENDIX B - BOOTHROYD AND DEWHURST DFA WORKSHEETS

Boothroyd and Dewhurst design for assembly analysis worksheet
 Current Saturn Design
 7/28/93

Item #	Item Name and Assembly Description	Number of Parts	Handling Code	Handling Time (sec)	Insertion Code	Insertion Time (sec)	Total Time (sec)	Total Cost (cents)*
1	Floating Clips - Attach to Panel	9	20	1.8	30	2	34.20	33.25
2	Door Panel - Place on frame	1	96	4	12	5	9.00	8.75
3	Clamps - Clamp panel to frame	2	00	1.13	00	1.5	5.26	5.11
4	Screws - Drive into floating clips	9	10	1.5	39	8	85.50	83.13
5	Clamps - Remove from door	2	00	1.13	00	1.5	5.26	5.11
Grand Totals							139.22	135.35

* Based on 0.972 cents/second (\$35.00/hr) labor rate.

Note: Assembly time estimates are computed from the Boothroyd and Dewhurst classification system for manual handling and insertion. While assembly time estimates may not be exact for the current process, this classification provides a useful method of quantifying and comparing assembly times for various conceptual designs to the original design.

Boothroyd and Dewhurst design for assembly analysis worksheet
 Flexing Concept
 7/28/93

Item #	Item Name and Assembly Description	Number of Parts	Handling Code	Handling Time (sec)	Insertion Code	Insertion Time (sec)	Total Time (sec)	Total Cost (cents)*
1	Floating Clips - Attach to Panel	2	20	1.8	30	2	7.60	7.39
2	Door panel - bend with flexing device	1	99	9	98	9	18.00	17.50
3	Door Panel - Place on frame and release	1	99	9	98	9	18.00	17.50
4	Screws - Drive into floating clips	2	10	1.5	39	8	19.00	18.47
Grand Totals							62.60	60.86

* Based on 0.972 cents/second (\$35.00/hr) labor rate.

Note: Assembly time estimates are computed from the Boothroyd and Dewhurst classification system for manual handling and insertion. While assembly time estimates may not be exact for the current process, this classification provides a useful method of quantifying and comparing assembly times for various conceptual designs to the original design.

Boothroyd and Dewhurst design for assembly analysis worksheet
Sliding Concept
7/28/93

Item #	Item Name and Assembly Description	Number of Parts	Handling Code	Handling Time (sec)	Insertion Code	Insertion Time (sec)	Total Time (sec)	Total Cost (cents)*
1	Floating Clips - Attach to Panel	2	20	1.8	30	2	7.60	7.39
2	Door Panel - Slide on frame	1	99	9	98	9	18.00	17.50
3	Screws - Drive into floating clips	2	10	1.5	39	8	19.00	18.47
Grand Totals							44.60	43.36

* Based on 0.972 cents/second (\$35.00/hr) labor rate.

Note: Assembly time estimates are computed from the Boothroyd and Dewhurst classification system for manual handling and insertion. While assembly time estimates may not be exact for the current process, this classification provides a useful method of quantifying and comparing assembly times for various conceptual designs to the original design.

Boothroyd and Dewhurst design for assembly analysis worksheet

Quarter Turn Fastener Concept

7/28/93

Item #	Item Name and Assembly Description	Number of Parts	Handling Code	Handling Time (sec)	Insertion Code	Insertion Time (sec)	Total Time (sec)	Total Cost (cents)*
1	Door Panel - Place on frame	1	96	4	12	5	9.00	8.75
2	Clamps - Clamp panel to frame	2	00	1.13	00	1.5	5.26	5.11
3	Quarter Turn Fasteners - Attach	9	10	1.5	31	5	58.50	56.88
4	Clamps - Remove from door	2	00	1.13	00	1.5	5.26	5.11
Grand Totals							78.02	75.85

* Based on 0.972 cents/second (\$35.00/hr) labor rate.

Note: Assembly time estimates are computed from the Boothroyd and Dewhurst classification system for manual handling and insertion. While assembly time estimates may not be exact for the current process, this classification provides a useful method of quantifying and comparing assembly times for various conceptual designs to the original design.

Boothroyd and Dewhurst design for assembly analysis worksheet
 Blind Rivet Concept
 7/28/93

Item #	Item Name and Assembly Description	Number of Parts	Handling Code	Handling Time (sec)	Insertion Code	Insertion Time (sec)	Total Time (sec)	Total Cost (cents)*
1	Door Panel - Place on frame	1	96	4	12	5	9.00	8.75
2	Clamps - Clamp panel to frame	2	00	1.13	00	1.5	5.26	5.11
3	Blind Rivet Fasteners - Attach	9	05	1.84	34	6	70.56	68.60
4	Clamps - Remove from door	2	00	1.13	00	1.5	5.26	5.11
Grand Totals							90.08	87.58

* Based on 0.972 cents/second (\$35.00/hr) labor rate.

Note: Assembly time estimates are computed from the Boothroyd and Dewhurst classification system for manual handling and insertion. While assembly time estimates may not be exact for the current process, this classification provides a useful method of quantifying and comparing assembly times for various conceptual designs to the original design.

Boothroyd and Dewhurst design for assembly analysis worksheet
Removable Rivet Concept

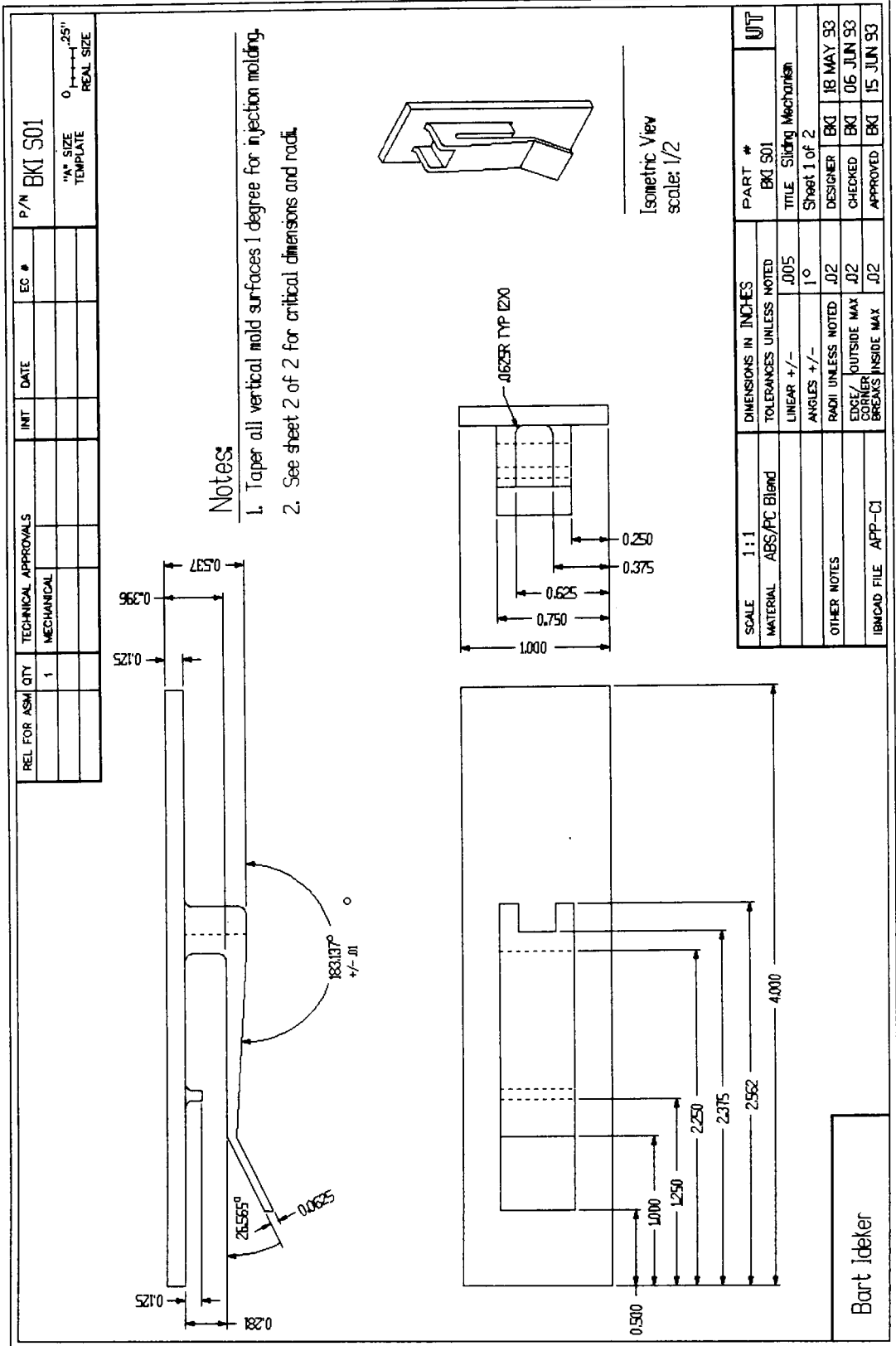
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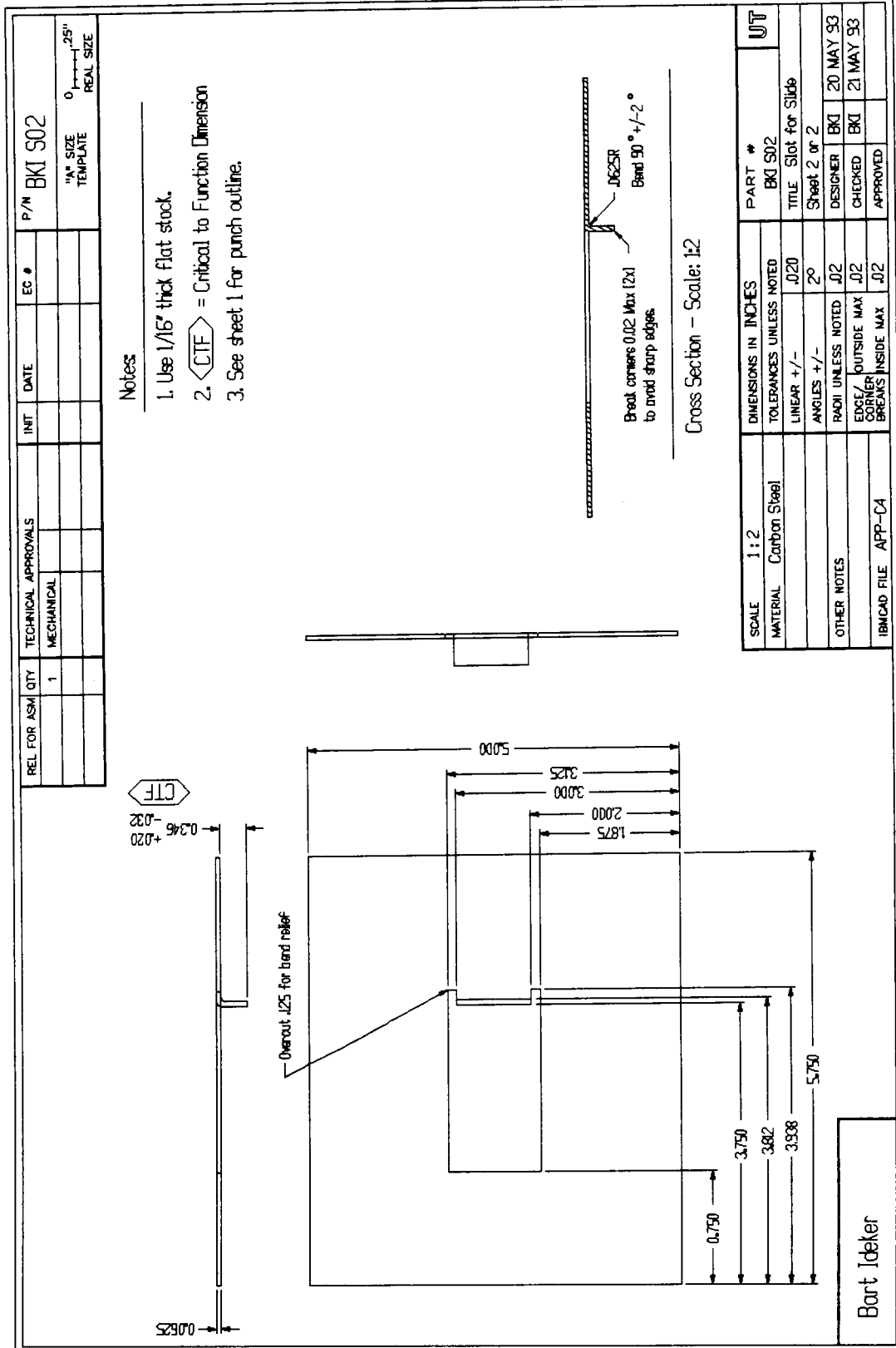
Item #	Item Name and Assembly Description	Number of Parts	Handling Code	Handling Time (sec)	Insertion Code	Insertion Time (sec)	Total Time (sec)	Total Cost (cents)*
1	Door Panel - Place on frame	1	96	4	12	5	9.00	8.75
2	Clamps - Clamp panel to frame	2	00	1.13	00	1.5	5.26	5.11
3	Removable Rivet Fasteners - Attach	9	05	1.84	31	5	61.56	59.85
4	Clamps - Remove from door	2	00	1.13	00	1.5	5.26	5.11
Grand Totals							81.08	78.83

* Based on 0.972 cents/second (\$35.00/hr) labor rate.

Note: Assembly time estimates are computed from the Boothroyd and Dewhurst classification system for manual handling and insertion. While assembly time estimates may not be exact for the current process, this classification provides a useful method of quantifying and comparing assembly times for various conceptual designs to the original design.

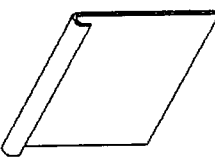
APPENDIX C - PROTOTYPE SHOP DRAWINGS





REL FOR ASM	QTY	TECHNICAL APPROVALS	INIT	DATE	EC #	P/N	BKI F02
	2	MECHANICAL					

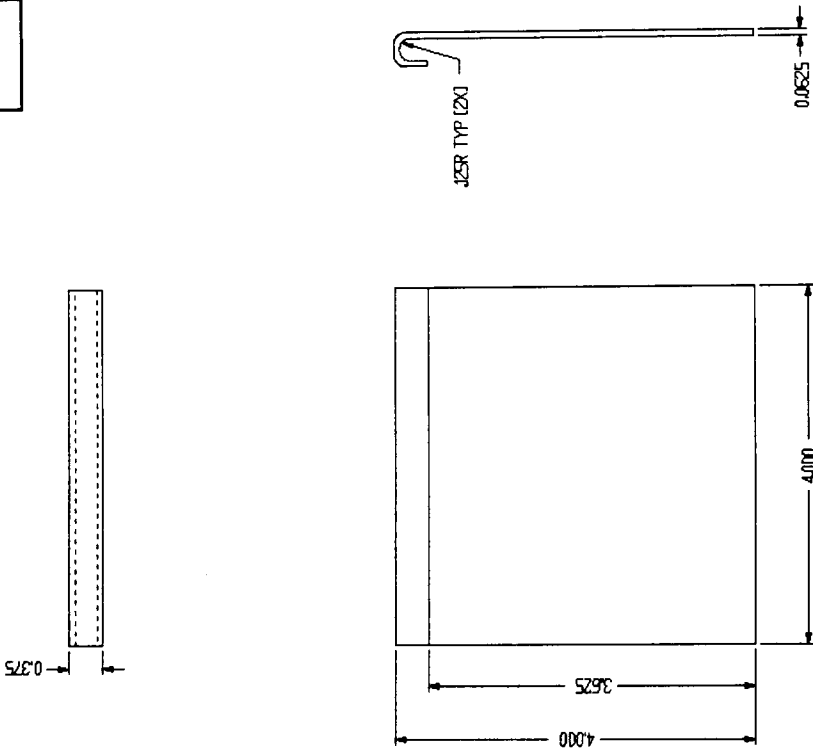
1/4" SIZE TEMPLATE	0	-----	.25"
REAL SIZE			



Isometric View
Not to Scale

NOTES:

1. USE 1/16 THICK FLAT STOCK
2. PART WILL BE SPOT WELDED TO LOWER AREA ON SATURN DOOR FRAME.



1/32" TYP (2X)

0.0625

4.000

3.625

4.000

Bart Ideler

REL FOR ASM		QTY	TECHNICAL APPROVALS		INT	DATE	EC #	P/N	BK1 F03
		1	MECHANICAL						
									"A" SIZE TEMPLATE
									0 $\frac{1}{16}$.25" REAL SIZE

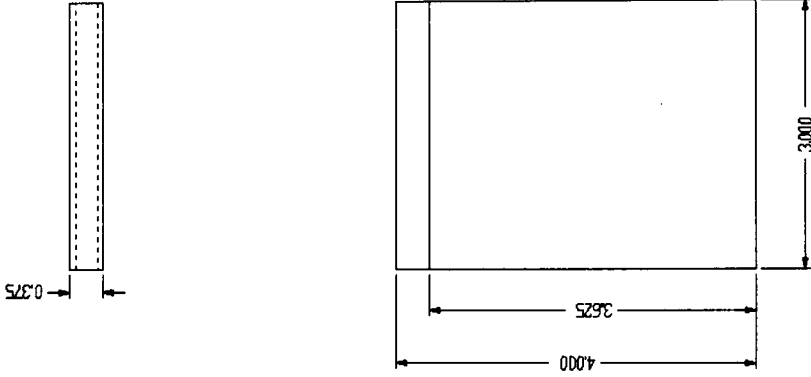
NOTES:

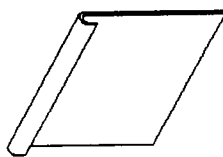
- USE 1/16 THICK FLAT STOCK
- SEE SHEET 2 OF 2 FOR BENDING DIMENSIONS

SCALE	1:2	DIMENSIONS IN INCHES	PART #	UT
MATERIAL	Carbon Steel	TOLERANCES UNLESS NOTED	BK1 F03	
		LINEAR +/-	.050	TITLE Lower Flexing Bracket 2
		ANGLES +/-	2°	Sheet 1 of 2
OTHER NOTES		RADI UNLESS NOTED	.0625	DESIGNER BK1 05 JUL 93
		EDGE/ OUTSIDE MAX	.02	CHECKED BK1 05 JUL 93
		CORNER BREAKS INSIDE MAX	.02	APPROVED BK1 05 JUL 93
IBMCAD FILE	APP-C7			

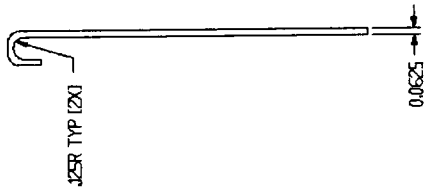
Bart Ideler

REL FOR ASM		QTY		TECHNICAL APPROVALS		INIT	DATE	EC #	P/N	BKI F04	
		1		MECHANICAL						"A" SIZE 0.25" TEMPLATE REAL SIZE	





Isometric View
Not to Scale



NOTES:

1. USE 1/16 THICK FLAT STOCK
2. PART WILL BE SPOT WELDED TO LOWER AREA ON SATURN DOOR FRAME.

SCALE	1:2	DIMENSIONS IN INCHES		PART #	UT
MATERIAL	Carbon Steel	TOLERANCES UNLESS NOTED		BKI F04	
		LINEAR +/-	.050	TITLE Lower Flange Bracket 2	
		ANGLES +/-	2°	Sheet 2 of 2	
OTHER NOTES		RADIO UNLESS NOTED	.0625	DESIGNER	BKI 05 JUL 93
		EDGE/CORNER BREAKS	OUTSIDE MAX .02	CHECKED	BKI 05 JUL 93
IBMCAD FILE	APP-C8		INSIDE MAX .02	APPROVED	BKI 05 JUL 93

Bart Ideler

REL FOR ASM QTY 3		TECHNICAL APPROVALS MECHANICAL		INT	DATE	EG #	P/N BK1 F07
NOTES: - USE 19 GAUGE FLAT STOCK (0.04375 in) - SEE SHEET 2 OF 2 FOR BENDING DIMENSIONS. - DOTTED LINES DENOTE LOCATION OF CENTER OF BENDING RADIUS.							

SCALE	1:1	DIMENSIONS IN INCHES	PART # BK1 F07	UT
MATERIAL	Carbon Steel			
19 Gauge (0.04375)		TOLERANCES UNLESS NOTED	TITLE UPPER Flexing Spring	
		LINEAR +/-	.050	Sheet 1 of 2
		ANGLES +/-	1°	DESIGNER BK1
OTHER NOTES		RADI UNLESS NOTED	.125	CHECKED BK1
		EDGE/OUTSIDE MAX	.02	APPROVED BK1
		BREAKS/INSIDE MAX	.02	
IBMCAD FILE APP-C11				

Bart Idder

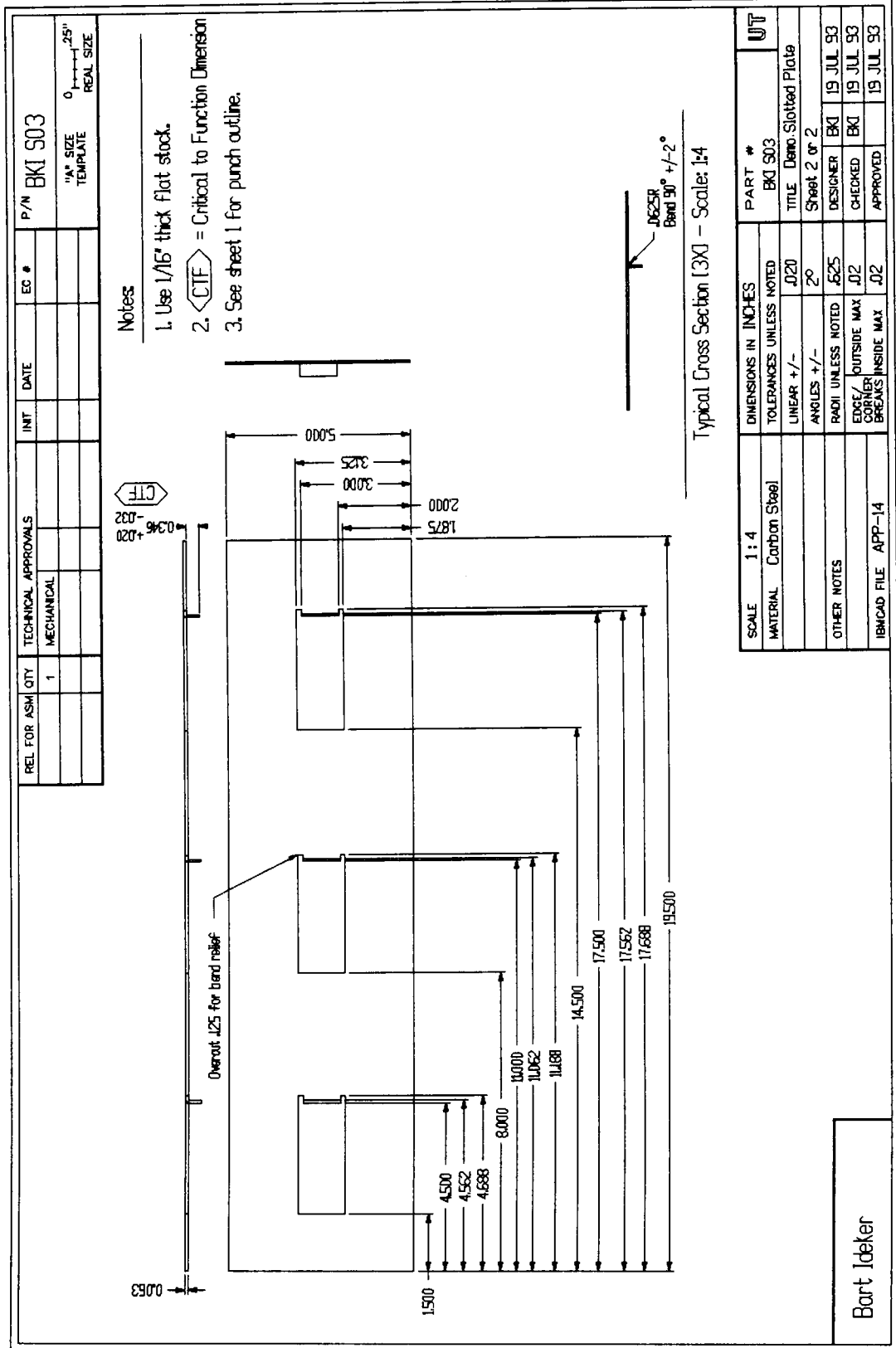


1. USE 19 GAUGE FLAT STOCK (0.04375 in.)
2. SEE SHEET 1 OF 2 FOR CUTTING OUTLINE.
3. ALL BENDING RADII .125 IN. MAX.

REL FOR ASM	QTY	TECHNICAL APPROVALS	INT	DATE	EC #	P/N
	3	MECHANICAL				BKI F07
						"A" SIZE TEMPLATE 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 REAL SIZE

SCALE	1:1	DIMENSIONS IN INCHES		PART #	UT
MATERIAL	Carbon Steel	TOLERANCES UNLESS NOTED		BK1 F07	
19 Gauge (0.04375)		LINEAR +/-	.050	TITLE	UPPER Flexing Spring
		ANGLES +/-	1°	Sheet 2 of 2	
OTHER NOTES		RADI UNLESS NOTED	.125	DESIGNER	BK1 12 JUL 93
		EDGE/ OUTSIDE MAX	.02	CHECKED	BK1 17 JUL 93
IBMGAD FILE	APP-C12	CORNER BREAKS INSIDE MAX	.02	APPROVED	BK1 17 JUL 93

Bart Ideker



APPENDIX D - TRANSFER MATRIX CODE AND RESULTS

Transfer Matrix Code Results for Tapered Slide Hook											
Geometry & Properties											
E = 420000											
b = 0.25											
h = 0.1											
mu = 0.4											
Deflection = 0.025											
Deflection = 0.05											
Deflection = 0.075											
length (in.)	Y = .025*	Y = .05*	Y = .075	Y = .025*	Y = .05*	Y = .075*	Y = .025*	Y = .05*	Y = .075*	Y = .025*	Y = .075*
Force (lbs)	Force (lbs)	Force (lbs)	Force (lbs)	Stress (psi)	Stress (psi)	Stress (psi)	Stress (psi)	Stress (psi)	Stress (psi)	Friction (lbs)	Friction (lbs)
0.125	336.00	672.00	1008.00	100800	201600	302400	134.40	201600	302400	403.20	268.80
0.15	194.44	388.89	583.33	70000	140000	210000	77.78	140000	210000	233.33	155.56
0.175	122.45	244.90	367.35	51429	102857	154286	48.98	102857	154286	146.94	97.96
0.2	82.03	164.06	246.09	39375	78750	118125	32.81	78750	118125	98.44	65.63
0.225	57.61	115.23	172.84	31111	62222	93333	23.05	62222	93333	69.14	46.09
0.25	42.00	84.00	126.00	25200	50400	75600	16.80	50400	75600	50.40	33.60
0.275	31.56	63.11	94.67	20826	41653	62479	12.62	41653	62479	37.87	25.24
0.3	24.31	48.61	72.92	17500	35000	52500	9.72	35000	52500	29.17	19.44
0.325	19.12	38.23	57.35	14911	29822	44734	7.65	29822	44734	22.94	15.29
0.35	15.31	30.61	45.92	12857	25714	38571	6.12	25714	38571	18.37	12.24
0.375	12.44	24.89	37.33	11200	22400	33600	4.98	22400	33600	14.93	9.96
0.4	10.25	20.51	30.76	9844	19688	29531	4.10	19688	29531	12.30	8.20
0.425	8.55	17.10	25.65	8720	17439	26159	3.42	17439	26159	10.26	6.84
0.45	7.20	14.40	21.60	7778	15556	23333	2.88	15556	23333	8.64	5.76
0.475	6.12	12.25	18.37	6981	13961	20942	2.45	13961	20942	7.35	4.90
0.5	5.25	10.50	15.75	6300	12600	18900	2.10	12600	18900	6.30	4.20
0.525	4.54	9.07	13.61	5714	11429	17143	1.81	11429	17143	5.44	3.63
0.55	3.94	7.89	11.83	5207	10413	15620	1.58	10413	15620	4.73	3.16
0.575	3.45	6.90	10.36	4764	9527	14291	1.38	9527	14291	4.14	2.76
0.6	3.04	6.08	9.11	4375	8750	13125	1.22	8750	13125	3.65	2.43
0.625	2.69	5.38	8.06	4032	8064	12096	1.08	8064	12096	3.23	2.15
0.65	2.39	4.78	7.17	3728	7456	11183	0.96	7456	11183	2.87	1.91
0.675	2.13	4.27	6.40	3457	6914	10370	0.85	6914	10370	2.56	1.71
0.7	1.91	3.83	5.74	3214	6429	9643	0.77	6429	9643	2.30	1.53
0.725	1.72	3.44	5.17	2996	5993	8989	0.69	5993	8989	2.07	1.38
0.75	1.56	3.11	4.67	2800	5600	8400	0.62	5600	8400	1.87	1.24
0.775	1.41	2.82	4.23	2622	5245	7867	0.56	5245	7867	1.69	1.13
0.8	1.28	2.56	3.85	2461	4922	7383	0.51	4922	7383	1.54	1.03
0.825	1.17	2.34	3.51	2314	4628	6942	0.47	4628	6942	1.40	0.93
0.85	1.07	2.14	3.21	2180	4360	6540	0.43	4360	6540	1.28	0.85
0.875	0.98	1.96	2.94	2057	4114	6171	0.39	4114	6171	1.18	0.78
0.9	0.90	1.80	2.70	1944	3889	5833	0.36	3889	5833	1.08	0.72
0.925	0.83	1.66	2.49	1841	3682	5522	0.33	3682	5522	1.00	0.66
0.95	0.77	1.53	2.30	1745	3490	5235	0.31	3490	5235	0.92	0.61
0.975	0.71	1.42	2.12	1657	3314	4970	0.28	3314	4970	0.85	0.57
1	0.66	1.31	1.97	1575	3150	4725	0.26	3150	4725	0.79	0.53

'SAVE "TAPER.BAS" WRITTEN BY BART IDEKER
 'THIS PROGRAM PERFORMS SEVERAL TRANSFER MATRIX OPERATIONS TO PREDICT
 'THE STATIC DEFLECTION OF A TAPERED CANTILEVER BEAM.

'ENTER CONSTANTS AND PERFORM ONE TIME CALCULATIONS

CLS

NM = 1000

DIM C11(NM), C12(NM), C13(NM), C14(NM), C21(NM), C22(NM), C23(NM), C24(NM)

DIM C31(NM), C32(NM), C33(NM), C34(NM), C41(NM), C42(NM), C43(NM), C44(NM)

DIM KTOR(NM), J(NM), M(NM), L(NM), K(NM), C15(NM), C25(NM), C35(NM), C45(NM)

DIM C55(NM), IMBALANCE(NM), IXX(NM), IZZ(NM), C51(NM), C52(NM), C53(NM)

DIM C54(NM), X1(NM), X2(NM), X3(NM), X4(NM), X5(NM)

DIM A(NM), HT(NM), I(NM)

LTOTAL = 1! 'TOTAL BEAM LENGTH IN INCHES

B = .5 'WIDTH OF BEAM

HBIG = .131 'HEIGHT OF BEAM AT CANTILEVER WALL

HLOW = .0762 'HEIGHT OF BEAM AT FREE END

HSTEP = (HBIG - HLOW) / NM 'INCREMENTAL STEP OF HEIGHT

PI = 3.141592654#

DEN = .282 'density

E = 420000 'modulus of elasticity

G = 210000 'modulus of rigidity

L = LTOTAL / NM 'length of one section

KSH = 10 * (1 + .5) / (12 + 11 * .5) 'shear factor correction

J1 = PI * DIA ^ 4 / 32

'DEFINE ARRAY PARAMETERS

FOR Q = 1 TO NM

HT(Q) = HBIG - Q * HSTEP 'HEIGHT AT POSITION Q

A(Q) = B * HT(Q) 'CROSS SECTIONAL AREA

I(Q) = B * HT(Q) ^ 3 / 12 'SECOND AREA MOMENT AT Q

M(Q) = L * A(Q) * DEN / 386 'MASS AT Q

K(Q) = 0 'SPRING CONSTANT AT Q

KTOR(Q) = 0 'TORSIONAL SPRING CONSTANT AT Q

J(Q) = M(Q) * DIA ^ 2 / 8 'SECOND MOMENT OF INERTIA AT Q

IMBALANCE(Q) = 0

IXX(Q) = M(Q) * (3 * DIA ^ 2 + 4 * L ^ 2) / 48

IZZ(Q) = M(Q) * DIA ^ 2 / 8

NEXT Q

'MAIN PROGRAM

'FOR LOOP TO DEFINE FREQUENCY, W

W = 0

'SET UP MATRICES C1 - CNM

FOR Q = 1 TO NM STEP 1

C11(Q) = 1:

C12(Q) = L:

C13(Q) = L ^ 2 / (2 * E * I(Q)):

C14(Q) = L ^ 3 / 6 / E / I(Q) - L / A(Q) / G * KSH

C15(Q) = 0

C21(Q) = 0

C22(Q) = 1:

```

C23(Q) = L / E / I(Q);
C24(Q) = L ^ 2 / 2 / E / I(Q)
C25(Q) = 0
C31(Q) = 0
C32(Q) = KTOR(Q) - W ^ 2 * (IZZ(Q) - IXX(Q))
C33(Q) = 1 + C23(Q) * C32(Q)
C34(Q) = -L + C24(Q) * C32(Q) 'ADJUSTED FOR PROBLEM (SHOULD BE +L)
C35(Q) = 0
C41(Q) = M(Q) * W ^ 2 - K(Q)
C42(Q) = L * C41(Q)
C43(Q) = C13(Q) * C41(Q)
C44(Q) = 1 + C41(Q) * C14(Q)
C45(Q) = IMBALANCE(NM) * W ^ 2
C55(Q) = 1
NEXT Q
'SET UP MATRIX MULTIPLICATION SUBROUTINE 5x5 (CZ*CZ-1)
Z = NM
C11A = C11(Z): C12A = C12(Z): C13A = C13(Z): C14A = C14(Z): C15A = C15(Z)
C21A = C21(Z): C22A = C22(Z): C23A = C23(Z): C24A = C24(Z): C25A = C25(Z)
C31A = C31(Z): C32A = C32(Z): C33A = C33(Z): C34A = C34(Z): C35A = C35(Z)
C41A = C41(Z): C42A = C42(Z): C43A = C43(Z): C44A = C44(Z): C45A = C45(Z)
C51A = C51(Z): C52A = C52(Z): C53A = C53(Z): C54A = C54(Z): C55A = C55(Z)

C11B = C11(Z - 1): C12B = C12(Z - 1): C13B = C13(Z - 1): C14B = C14(Z - 1): C15B = C15(Z - 1)
C21B = C21(Z - 1): C22B = C22(Z - 1): C23B = C23(Z - 1): C24B = C24(Z - 1): C25B = C25(Z - 1)
C31B = C31(Z - 1): C32B = C32(Z - 1): C33B = C33(Z - 1): C34B = C34(Z - 1): C35B = C35(Z - 1)
C41B = C41(Z - 1): C42B = C42(Z - 1): C43B = C43(Z - 1): C44B = C44(Z - 1): C45B = C45(Z - 1)
C51B = C51(Z - 1): C52B = C52(Z - 1): C53B = C53(Z - 1): C54B = C54(Z - 1): C55B = C55(Z - 1)
GOSUB 1000
'LOOP THROUGH ALL MATRIX MULTIPLICATIONS FROM CZ TO C1
FOR H = (Z - 2) TO 1 STEP -1
  C11A = C11F: C12A = C12F: C13A = C13F: C14A = C14F: C15A = C15F
  C21A = C21F: C22A = C22F: C23A = C23F: C24A = C24F: C25A = C25F
  C31A = C31F: C32A = C32F: C33A = C33F: C34A = C34F: C35A = C35F
  C41A = C41F: C42A = C42F: C43A = C43F: C44A = C44F: C45A = C45F
  C51A = C51F: C52A = C52F: C53A = C53F: C54A = C54F: C55A = C55F

  C11B = C11(H): C12B = C12(H): C13B = C13(H): C14B = C14(H): C15B = C15(H)
  C21B = C21(H): C22B = C22(H): C23B = C23(H): C24B = C24(H): C25B = C25(H)
  C31B = C31(H): C32B = C32(H): C33B = C33(H): C34B = C34(H): C35B = C35(H)
  C41B = C41(H): C42B = C42(H): C43B = C43(H): C44B = C44(H): C45B = C45(H)
  C51B = C51(H): C52B = C52(H): C53B = C53(H): C54B = C54(H): C55B = C55(H)
  GOSUB 1000
NEXT H
X1(0) = 0: X2(0) = 0: X4(0) = 5.72: X3(0) = X4(0) * LTOTAL: X5(0) = 1
Z = 0
'PRINT USING "Z = ## Y = #.#### THETA = ##.#### MOMENT = ##.#### SHEAR = ####"; Z;
X1(Z); X2(Z); X3(Z); X4(Z)

X1CHECK = C11F * X1(0) + C12F * X2(0) + C13F * X3(0) + C14F * X4(0) + C15F * X5(0)
X2CHECK = C21F * X1(0) + C22F * X2(0) + C23F * X3(0) + C24F * X4(0) + C25F * X5(0)

```

$X3CHECK = C31F * X1(0) + C32F * X2(0) + C33F * X3(0) + C34F * X4(0) + C35F * X5(0)$
 $X4CHECK = C41F * X1(0) + C42F * X2(0) + C43F * X3(0) + C44F * X4(0) + C45F * X5(0)$
 $X5CHECK = C51F * X1(0) + C52F * X2(0) + C53F * X3(0) + C54F * X4(0) + C55F * X5(0)$

FOR Z = 1 TO NM

$X1(Z) = C11(Z) * X1(Z - 1) + C12(Z) * X2(Z - 1) + C13(Z) * X3(Z - 1) + C14(Z) * X4(Z - 1) + C15(Z) * X5(Z - 1)$

$X2(Z) = C21(Z) * X1(Z - 1) + C22(Z) * X2(Z - 1) + C23(Z) * X3(Z - 1) + C24(Z) * X4(Z - 1) + C25(Z) * X5(Z - 1)$

$X3(Z) = C31(Z) * X1(Z - 1) + C32(Z) * X2(Z - 1) + C33(Z) * X3(Z - 1) + C34(Z) * X4(Z - 1) + C35(Z) * X5(Z - 1)$

$X4(Z) = C41(Z) * X1(Z - 1) + C42(Z) * X2(Z - 1) + C43(Z) * X3(Z - 1) + C44(Z) * X4(Z - 1) + C45(Z) * X5(Z - 1)$

PRINT USING "Z = ## Y = ##### THETA = ##### MOMENT = ##### SHEAR = #####"; Z;
 X1(Z); X2(Z); X3(Z); X4(Z)

NEXT Z

LSTUB = .3 'LENGTH OF STUB BEAM (GOES INTO WALL)

ISTUB = .000218709# 'AREA MOMENT OF INERTIA FOR STUB

YSTUB = LSTUB * X4(0) * LTOTAL ^ 2 / E / ISTUB 'DEFLECTION OF MAIN BEAM DUE TO STUB ANGLE

Z = NM

PRINT " TRANSFER MATRIX CODE SOLUTION OF TAPERED BEAM DEFLECTION"

PRINT USING " FORCE LOCATION = ### IN. Y = ##### IN. F = ###.## STRESS = ##### PSI"; Z * L;
 X1(Z) + YSTUB; X4(Z); X4(Z) * LTOTAL * HBIG / 2 / (B * HBIG ^ 3) * 12

'LPRINT USING " FORCE LOCATION = ### IN. Y = ##### IN. F = ###.## STRESS = ##### PSI"; Z *
 L; X1(Z) + YSTUB; X4(Z); X4(Z) * LTOTAL * HBIG / 2 / (B * HBIG ^ 3) * 12

END

'SUBROUTINE - MATRIX MULTIPLICATION - MULTIPLIES 5x5 MATRIX (A & B)

1000 C11F = C11A * C11B + C12A * C21B + C13A * C31B + C14A * C41B + C15A * C51B

C12F = C11A * C12B + C12A * C22B + C13A * C32B + C14A * C42B + C15A * C52B

C13F = C11A * C13B + C12A * C23B + C13A * C33B + C14A * C43B + C15A * C53B

C14F = C11A * C14B + C12A * C24B + C13A * C34B + C14A * C44B + C15A * C54B

C15F = C11A * C15B + C12A * C25B + C13A * C35B + C14A * C45B + C15A * C55B

C21F = C21A * C11B + C22A * C21B + C23A * C31B + C24A * C41B + C25A * C51B

C22F = C21A * C12B + C22A * C22B + C23A * C32B + C24A * C42B + C25A * C52B

C23F = C21A * C13B + C22A * C23B + C23A * C33B + C24A * C43B + C25A * C53B

C24F = C21A * C14B + C22A * C24B + C23A * C34B + C24A * C44B + C25A * C54B

C25F = C21A * C15B + C22A * C25B + C23A * C35B + C24A * C45B + C25A * C55B

C31F = C31A * C11B + C32A * C21B + C33A * C31B + C34A * C41B + C35A * C51B

C32F = C31A * C12B + C32A * C22B + C33A * C32B + C34A * C42B + C35A * C52B

C33F = C31A * C13B + C32A * C23B + C33A * C33B + C34A * C43B + C35A * C53B

C34F = C31A * C14B + C32A * C24B + C33A * C34B + C34A * C44B + C35A * C54B

C35F = C31A * C15B + C32A * C25B + C33A * C35B + C34A * C45B + C35A * C55B

C41F = C41A * C11B + C42A * C21B + C43A * C31B + C44A * C41B + C45A * C51B

C42F = C41A * C12B + C42A * C22B + C43A * C32B + C44A * C42B + C45A * C52B
C43F = C41A * C13B + C42A * C23B + C43A * C33B + C44A * C43B + C45A * C53B
C44F = C41A * C14B + C42A * C24B + C43A * C34B + C44A * C44B + C45A * C54B
C45F = C41A * C15B + C42A * C25B + C43A * C35B + C44A * C45B + C45A * C55B

C51F = C51A * C11B + C52A * C21B + C53A * C31B + C54A * C41B + C55A * C51B
C52F = C51A * C12B + C52A * C22B + C53A * C32B + C54A * C42B + C55A * C52B
C53F = C51A * C13B + C52A * C23B + C53A * C33B + C54A * C43B + C55A * C53B
C54F = C51A * C14B + C52A * C24B + C53A * C34B + C54A * C44B + C55A * C54B
C55F = C51A * C15B + C52A * C25B + C53A * C35B + C54A * C45B + C55A * C55B

RETURN

APPENDIX E - PROTOTYPE TESTING RESULTS

Assembly Time Testing Results

Test#	Time (seconds)		
	Current Design	Sliding Design	Flexing Design
1	136	51	64
2	141	50	66
3	144	55	65
4	149	48	55
5	142	36	57
6	139	43	49
7	148	44	56
8	144	41	57
9	141	45	49
10	143	49	60
Mean	142.7	46.2	57.8
Standard Error	1.22972445	1.743559577	1.913693346
Median	142.5	46.5	57
Mode	141	#N/A	57
Standard Deviation	3.888730155	5.513619501	6.051629716
Variance	15.12222222	30.4	36.62222222
Kurtosis	0.040973306	0.02837068	-0.958309961
Skewness	0.098628986	-0.308446728	-0.136717966
Range	13	19	17
Minimum	136	36	49
Maximum	149	55	66
Sum	1427	462	578
Count	10	10	10

24 Hour, 150F Relaxation Test Results

Hour	Clamping Force (lbs.)	Measurements (in.)
0	4.25	0.412
3.5	2.1	0.489
6.15	1.5	0.498
9	1.3	0.5
24	1.25	0.5

24 Hour, 180F Relaxation Test Results

Hour	Clamping Force (lbs.)	Measurements (in.)
0	5	0.339
3.5	1.5	0.485
6.15	0.5	0.512

48 Hour, 130F Relaxation Results

Hour	Clamping Force (lbs.)	Measurements (in.)
0	4.9	0.331
1	3.7	0.39
2.75	3.3	0.401
8	3.1	0.415
20.5	2.6	0.427
23.5	2.6	0.43
30.5	2.6	0.431
44.5	2.4	0.439
48	2.4	0.44

30 Day Room Temperature Relaxation Results

Date	Measurement (in.)
6/9/93	0.382
6/10/93	0.387
6/11/93	0.389
6/12/93	0.39
6/13/93	0.391
6/14/93	0.392
6/15/93	0.393
6/16/93	0.392
6/17/93	0.393
6/18/93	0.394
6/19/93	0.394
6/20/93	0.394
6/21/93	0.395
6/22/93	0.395
6/23/93	0.395
6/24/93	0.396
6/25/93	0.396
6/26/93	0.396
6/27/93	0.396
6/28/93	0.397
6/29/93	0.397
6/30/93	0.397
7/1/93	0.397
7/2/93	0.397
7/3/93	0.398
7/4/93	0.398
7/5/93	0.398
7/6/93	0.398
7/7/93	0.398
7/8/93	0.398
7/9/93	0.398

Vita

Barton Kirk Ideker was born in Washington, DC on January 18, 1968. He moved to Erwin, Tennessee in 1969 and resided in East Tennessee for the following 24 years. In May, 1986 he was graduated from Science Hill High School in Johnson City, Tennessee. The following September he enrolled at the University of Tennessee in Knoxville. He earned a Bachelor of Science degree in Mechanical Engineering in May, 1992 and immediately began working on a Master of Science in Mechanical Engineering. In August of 1993, he completed the Master of Science Degree. Throughout his Senior year and graduate school, he was involved in the Superior Engineering Design Program.

He began working at McDonald's shortly after his sixteenth birthday and continued to work part time throughout his high school years. He worked several summers breaks during his undergraduate years at Standard Forms, a small business printer, in Johnson City. In April, 1988, he began co-oping with Kesterson Construction, a heavy industrial construction company, and continued to alternate semesters of working and attending classes until August of 1991. He is currently employed at General Electric Lighting Systems in Hendersonville, North Carolina as a design engineer.

He is a brother in good standing of Lambda Chi Alpha - general college fraternity and an avid Tennessee Volunteer football fan.