INTRODUCTION

Forming pressures used in the traditional high pressure hydroform process are calculated based on the hoop stress required to yield the tube at the corner radius as it is being formed. Because forming is based upon yielding the material, forming high strength steels or heavy wall tube requires the increased cost of operating at higher internal pressures. Large tube components can limit the forming pressures used because of the die forces developed during forming. Usually held by hydraulic presses, these forces increase significantly when forming large components at high pressures.

Pressure Sequence Hydroforming has proven itself capable of providing the design flexibility and production process robustness necessary to meet the high standards demanded by the automobile industry. The success of the applications to date has hinged on providing a product that meets or exceeds all the customers expectations. This can only be accomplished when all the stakeholders are involved with the design as it develops. Receiving and acting upon input from the customer, manufacturing, suppliers, quality, design, and purchasing is necessary if the most efficient design is to be developed.

TRADITIONAL HIGH PRESSURE HYDROFORMING

Traditional hydroforming systems increase the internal tube pressure until the hoop stress at the corner radius of the cross section is higher than the material yield strength. In so doing, the tube fills the corner radius areas of the die by locally stretching or expanding the tube wall. Figure 1 shows the cross section of a tube in a die where a complex shaped die closes on a tube without pinching because the tube is smaller than the die cavity.

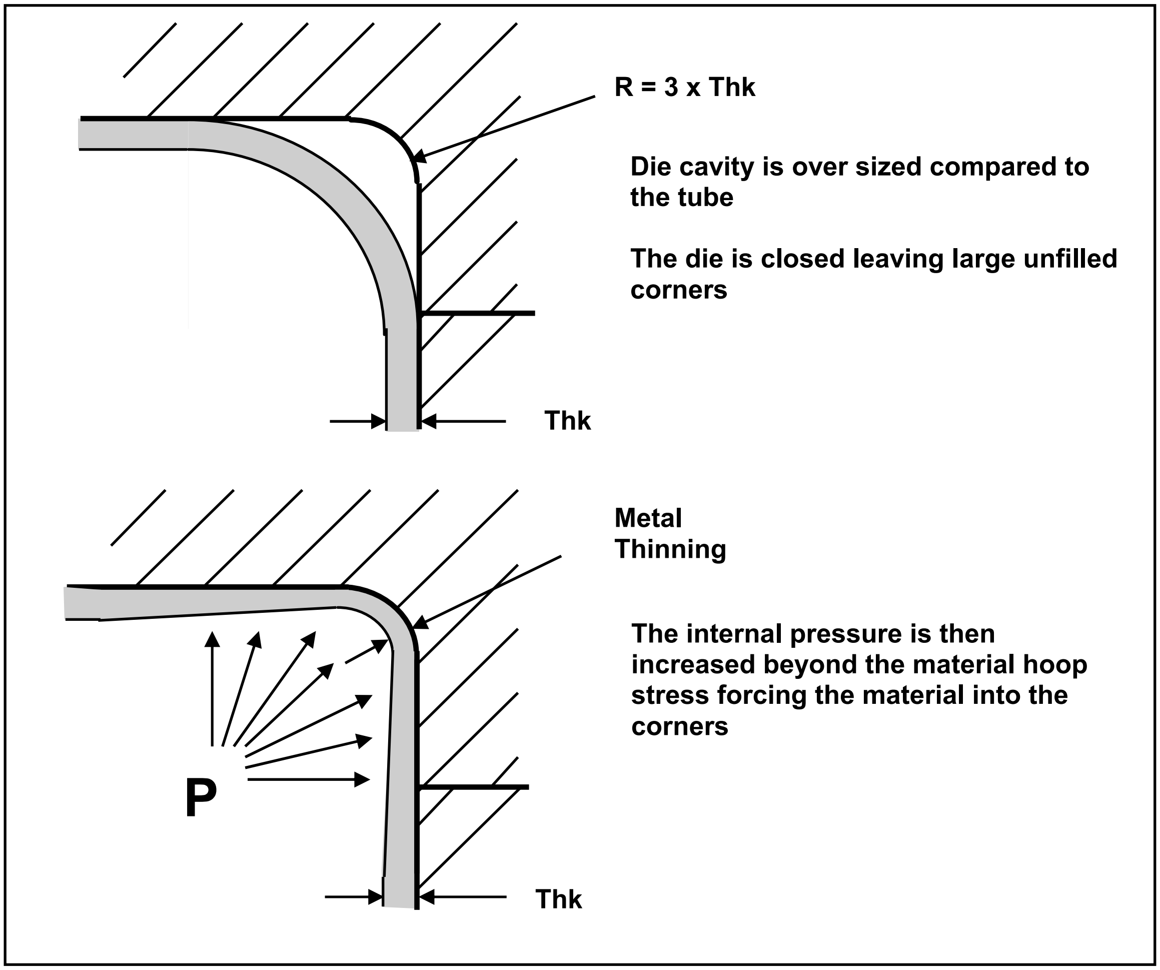

Figure 1 – Traditional High Pressure Forming - Corner Forming Mechanism

The use of high internal pressures results in the creation of significant friction between the tube wall and the die surface. Once the tube wall makes contact with the die, friction will tend to oppose any further movement. Thus the tube will stretch less in the areas where it is in contact with the die, and more in the corners and areas which do not contact the cavity surface. The result of this friction is uneven wall thickness distribution around the finished part cross section, (refer to figure 2). The tube material must have adequate elongation to withstand the thinning that occurs without rupturing. When using high strength steels or aluminum, bursting during the forming process can be a significant problem because of the material's lower forming limits.

When forming a given cross section shape using only internal pressure, the smallest corner radius to be formed will govern the amount of pressure required for the entire part. The formula below is used to determine the amount of pressure required to fully form a cross section. The material yield strength used must be the maximum value of the material as seen in the tube plus a factor due to the strain hardening which will occur during the hydroforming operation.

$$\text{Forming Pressure}_{\text{internal}} = \frac{\text{Max Material Yield Strength} \quad \text{X} \quad \text{Max Material Thickness}}{\text{Min Inside Corner Radius}}$$

Tube expansion (beyond the 3-5% typically required to form the corner radius) is possible during high pressure hydroforming but requires the use of tube materials with high elongation and oftentimes in-process annealing. Expansion at the ends of the tube using axial end feed in the hydroforming die is also commonly employed during high pressure forming.

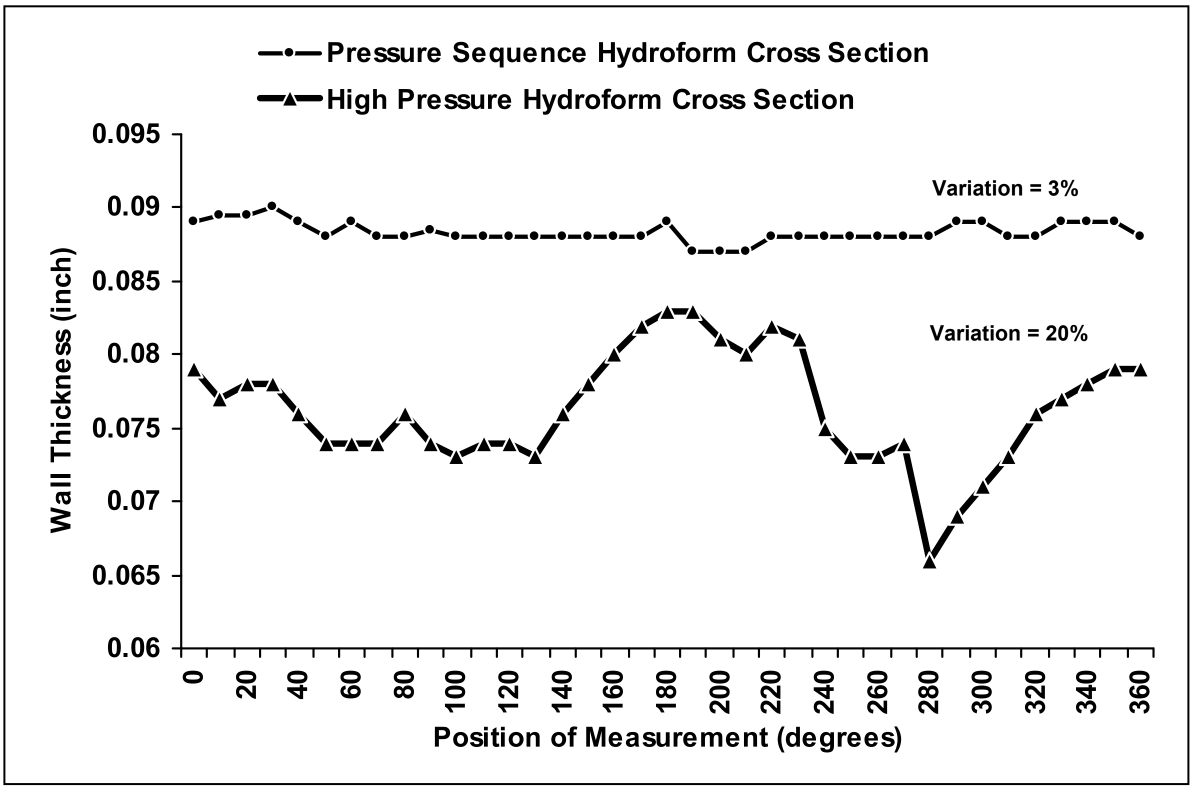

Figure 2 - Wall Thickness distribution after hydroforming

PRESSURE SEQUENCE HYDROFORMING

Pressure Sequence Hydroforming (PSH) was born from the need to economically form complex cross section shapes with tight corners using commercially available ERW steel tubing. Increased formability has been achieved by using a first stage pressure while the die is being closed, and a second high pressure stage after the die is fully closed.

Pressure Sequence Hydroforming forms the part shape by forcing the tube to flow into the corner areas of the die without stretching or expanding the tube to fill the die cavity. Exceeding the yield limit of the tube material in a bending mode forms the corner radius area. This is contrary to traditional high pressure hydroforming systems which fill the corners in a tensile mode. Since the tube forming is being controlled as the die is closing, the tendency for the tube to pinch at the die split line, as is common with traditional high pressure hydroforming, is virtually eliminated.

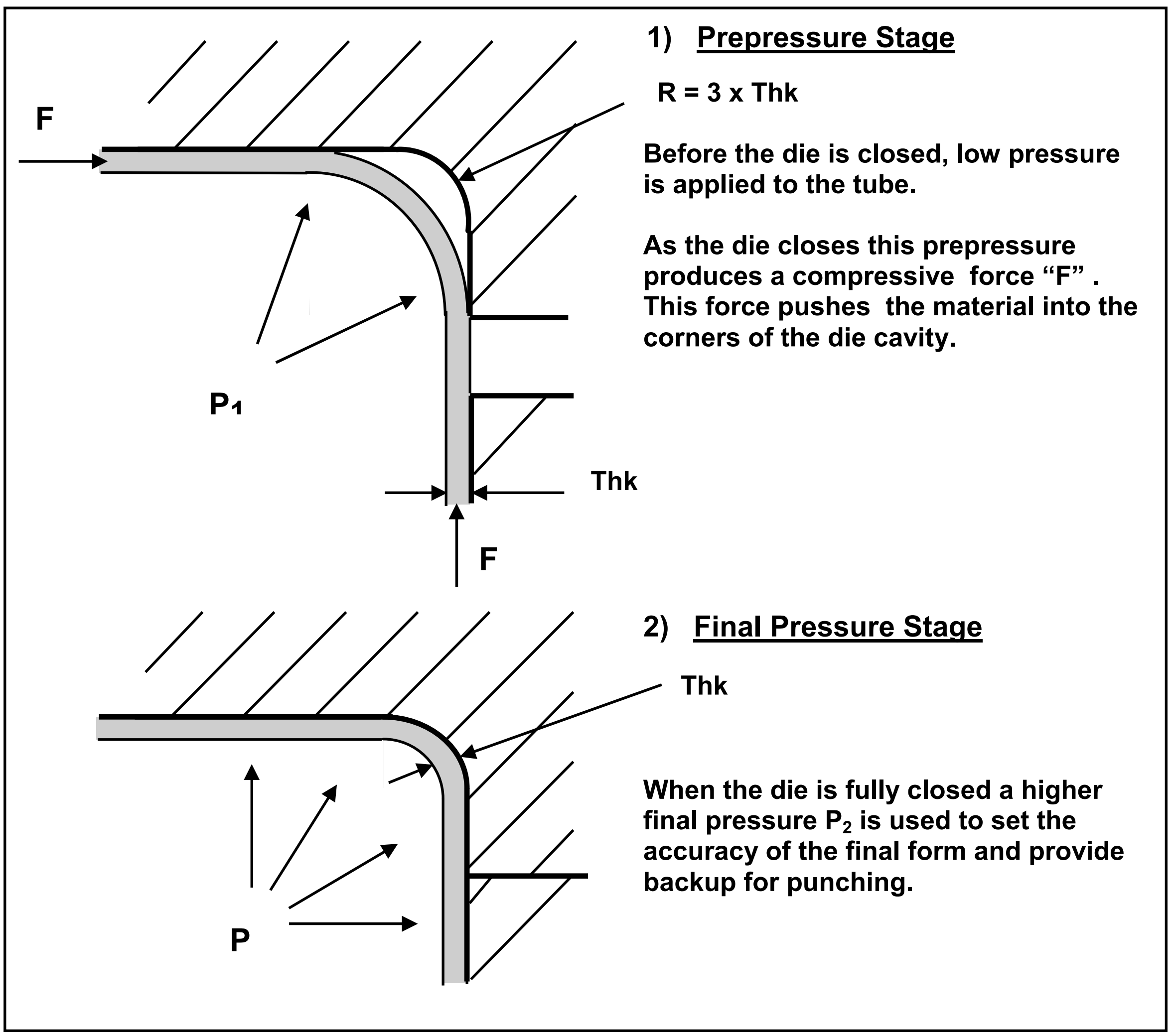

Figure 3 – Pressure Sequence Hydroforming - Corner Forming Mechanism

Figure 3 shows the die corner and how the pressure forms the radius in the tube by pushing the tube into the corner area. The free flow of metal in direction "F" allows an outside corner radius to be formed as small as three times metal thickness. During the first forming stage the internal tube pressure is kept low resulting in reduced friction. This is important as it allows the metal to slide along the die surface and into the corner areas. The final cross section has the same material thickness distribution as was present when the tube entered the die (see figure 2).

After forming a tube using Pressure Sequence Hydroforming (PSH) the average wall thickness of the formed part will be equal to that of the starting tube. The part formed using high pressure hydroforming will have an average wall thickness below that of the starting tube (refer to figure 2). This fact allows PSH to start with a thinner tube wall than traditional hydroforming while producing a stronger part.

After completion of the first stage, a higher internal pressure is applied to completely form the flat sides of the tube cross section, and provide support for in-die hole piercing. Since the cross section corners are formed by the closing action of the press, the internal pressure required to completely form the cross section is not governed by that which is required to form the corners. For this reason Pressure Sequence Hydroforming is able to form complex cross section shapes with tight corner radii without using high fluid pressures.

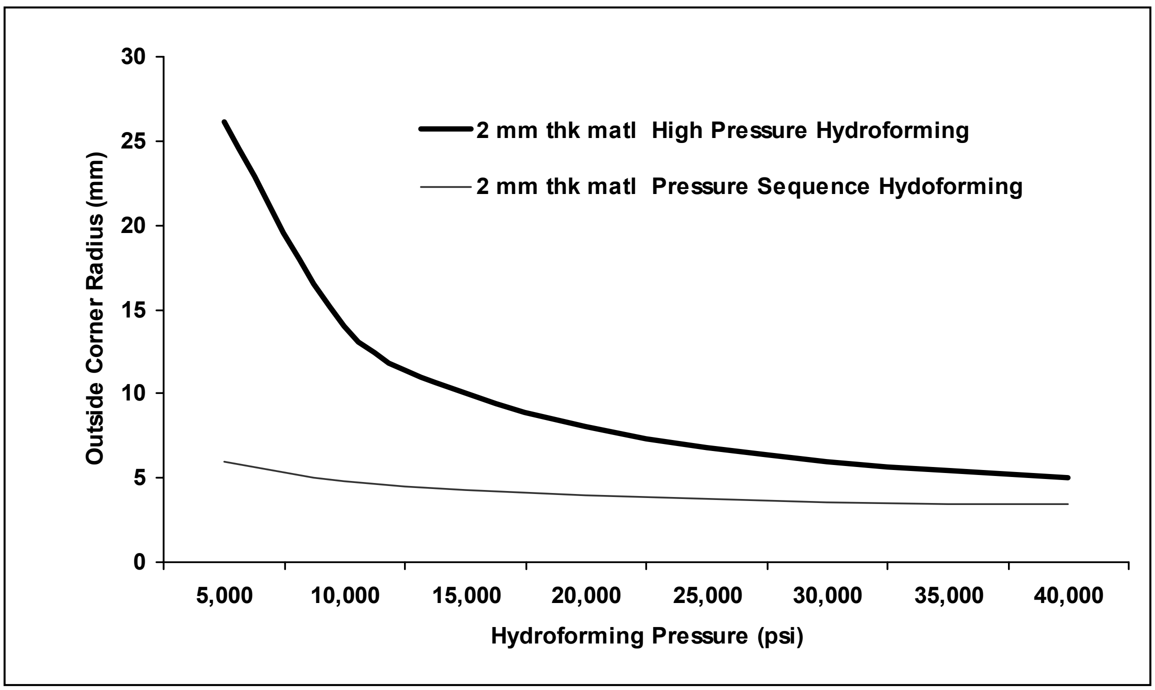

Figure 4 - Graph of Outside corner radius vs Hydroforming Pressure for 60,000 psi yield strength material

The combination of hydraulic and mechanical forces used to form the corners means that Pressure Sequence Hydroforming does not require the high internal pressures used in traditional tube hydroforming. The graph in figure 4 shows that as little as 5,000 psi internal pressure is all that is required to form a 6 mm (3 times thk) outside corner radius in a tube with 2 mm wall thickness and 60,000 psi yield strength. While PSH does not need high internal pressures to form corners, it can be combined with a high pressure system to offer locally expanded cross sections. When this is done the corner formed in the expanded areas of the part are governed by the capabilities of traditional high pressure hydroforming.

The action of pushing the material into the cross section corners makes Pressure Sequence Hydroforming ideally suited to forming low elongation materials without concern of cracking or necking the tube wall. This makes the process well suited to forming galvanized or precoated materials. Tests using low formability materials have been conducted using a production die designed for use with mild steel tubing. A variety of tube materials including Aluminum and Ultra High Strength Steel have been successfully substituted for the mild steel without making any process parameter changes.

Wall Thickness	Outside Corner Rad	Steel Spec	Required Pressure Sequence Forming Pressure	Required High Pressure Forming Pressure
2 mm	9 mm (4.7T)	1010	360 bar	950 bar
3 mm	9 mm (3.2T)	1010	360 bar	1660 bar
6 mm	9 mm (1.5T)	1026	400 bar	6660 bar

Figure 5 – The effect of increasing material thickness on forming pressure

Experiments have also been conducted with the substitution of different material thicknesses into an existing tool. One of these tests yielded the successful formation of tube materials which were three times the thickness for which the tool was designed (refer to figure 5) using only a minimal increase in forming pressure. As the cross section corner radius stays the same as ever-thicker material is introduced into the tool, the net effect was to form a corner with a radius equivalent to 1.5 times the material thickness. As the table of values in figure 5 indicates, using only internal pressure to form the same cross section would require approximately 3 to 16 times the internal pressure.

CURRENT APPLICATIONS

Chrysler Minivan Instrument Panel Beam

The Chrysler “S” Body Instrument Panel Beam was the first high volume application for Pressure Sequence Hydroforming. Starting in the 1991 model year a hydroformed tube replaced a two piece stamped and welded clamshell style part resulting in significant weight savings due to the elimination of weld flanges. Removing the weld flanges from the cross car beam also eliminated concerns of electrical wire chaffing which resulted in reduced product warranty costs. The flexibility to bend and change the cross section shape throughout the length of the beam provided superior packaging and NVH characteristics.

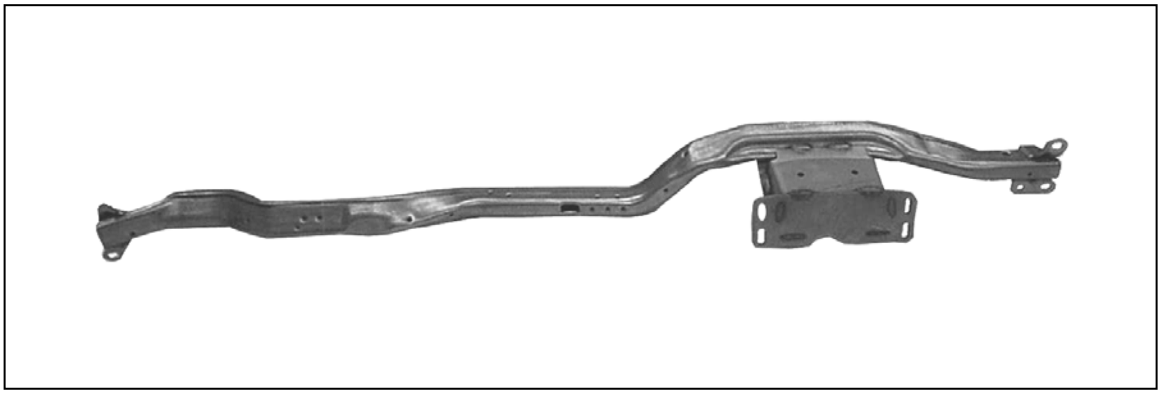

Figure 6 – DaimlerChrysler Mini-van Instrument Panel Beam

Efforts began with the first generation design to reduce assembly manufacturing costs and improve the instrument panel dimensional stability by utilizing self tapping screws for many of the I/P attachments. Using punch units in the hydroform die, extruded holes are formed in the tube, which are compatible with many types of self-threading screws. Forming the holes in the hydroform die eliminated multiple post piercing operations and did away with the purchase of weld or pierce nuts.

To date over 4.5 million Instrument Panel Beams have been formed using Pressure Sequence Hydroforming, with current production of the third generation Instrument Panel Beam Assembly continuing at a rate of over 700,000 units per year. The entire volume is formed using a dedicated production line utilizing a single cavity die operating at a 17 second cycle time on a two shift five day a week basis.

Ford Aerostar Instrument Panel Reinforcement

A hydroformed Instrument panel reinforcement replaced a proposed three piece stamped and welded assembly resulting in a 3 pound weight reduction and vastly improved NVH characteristics. The hydroformed beam included a number of unique design features such as the use of access holes to allow for the spot welding of detail brackets to the tube and round cross sections at the ends of the part which eliminated the post hydroform trim operation and engineered scrap.

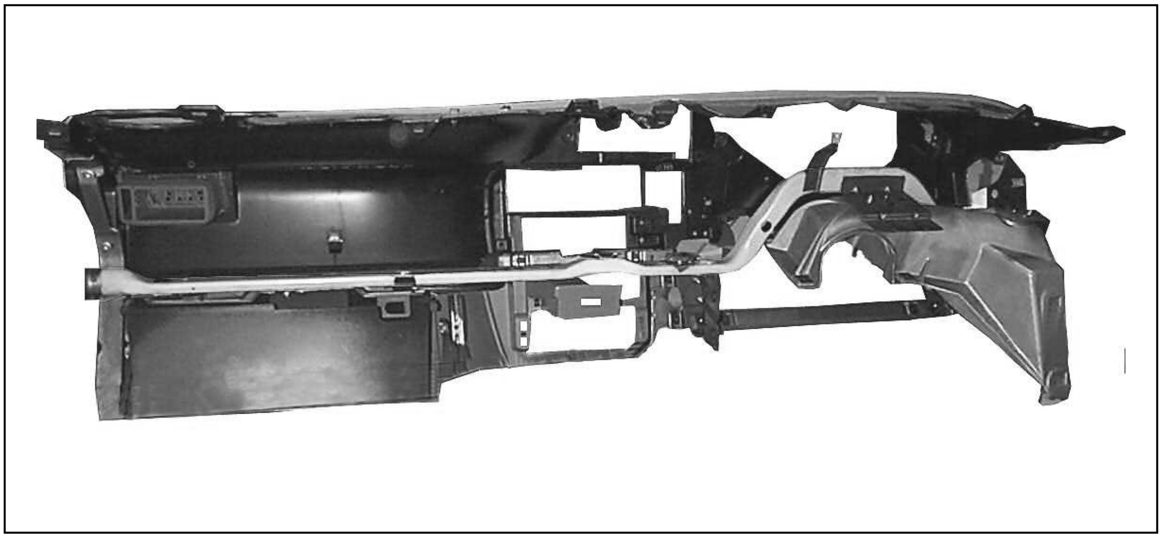

Figure 7 – Ford Aerostar Instrument Panel Reinforcement

The hydroformed beam entered production for the 1992 model year and was utilized up until the end of Aerostar production. The part included 25 holes ranging in size from as large as 22 mm in diameter down to 3 mm in diameter. Of these holes, 24 were formed in the hydroform die and one was post pierced using a small air/oil punch unit. The tool design featured the development of punches that split the slugs in two made it possible to form 22 mm diameter holes with the resulting slugs retained in a cross section which is only 18 mm high.

Ford CDW 27 Engine Cradle

The Ford CDW platform was the first to utilize a hydroformed engine cradle perimeter tube. The assembly was introduced on the European Ford Mondeo for the 1993 Model year and then launched in North America for the 1995 Ford Contour / Mercury Mystique. A single hydroformed tube replaced six large stamped and welded components resulting in significant weight and cost savings.

The finished hydroform tube includes 21 holes pierced during forming, some with stringent profile and deformation tolerances due to the function of the hole such as paint drain and clip attachment. Tight part packaging required moving die sections to form reentrant cross sections in the area of the control arm bushings.

The application of Pressure Sequence Hydroforming facilitated the first use of High Strength Low Alloy steel tube in a high volume chassis part. To date over 3.0 million CDW 27 cradles have been produced in Europe and North America. As with the instrument panel beams the engine cradle also makes use of self-tapping screws for attaching detail parts to the tube.

Figure 8 – Ford CDW 27 Engine Cradle Assembly

Dodge Ram Pickup Radiator Enclosure Assembly

The redesigned 1994 Dodge Ram Pickup truck includes the first use of a hydroformed radiator closure assembly. Two hydroformed tubes replaced eight large stampings and their required assembly welding operations. The hydroformed assembly reduced the number of components from 17 to 10, which resulted in a 9.0 pound weight reduction and $6.0 million in savings to the program.

The wide range of options available on the vehicle presented a significant challenge to the product designers as it was necessary to design a single assembly that was capable of providing the needs of the entire truck line. This included engine cooling packages for V6, V8, and V10 gasoline engines as well as an intercooled turbo charged diesel engine. The design flexibility afforded by Pressure Sequence Hydroforming allows for the formation of 57 holes in the lower tube and 29 in the upper during the hydroforming process. Thus, all the required holes and attachments are formed in every tube, eliminating the requirement for multiple part variations.

The upper tube includes a unique pair of holes formed in the hydroform tool. The function of the holes (hood latch safety catch) required the complete removal of the slugs from the tube. This is accomplished in the hydroform die using a modified sequential punch system to form the holes and extract the slugs during the part forming operation.

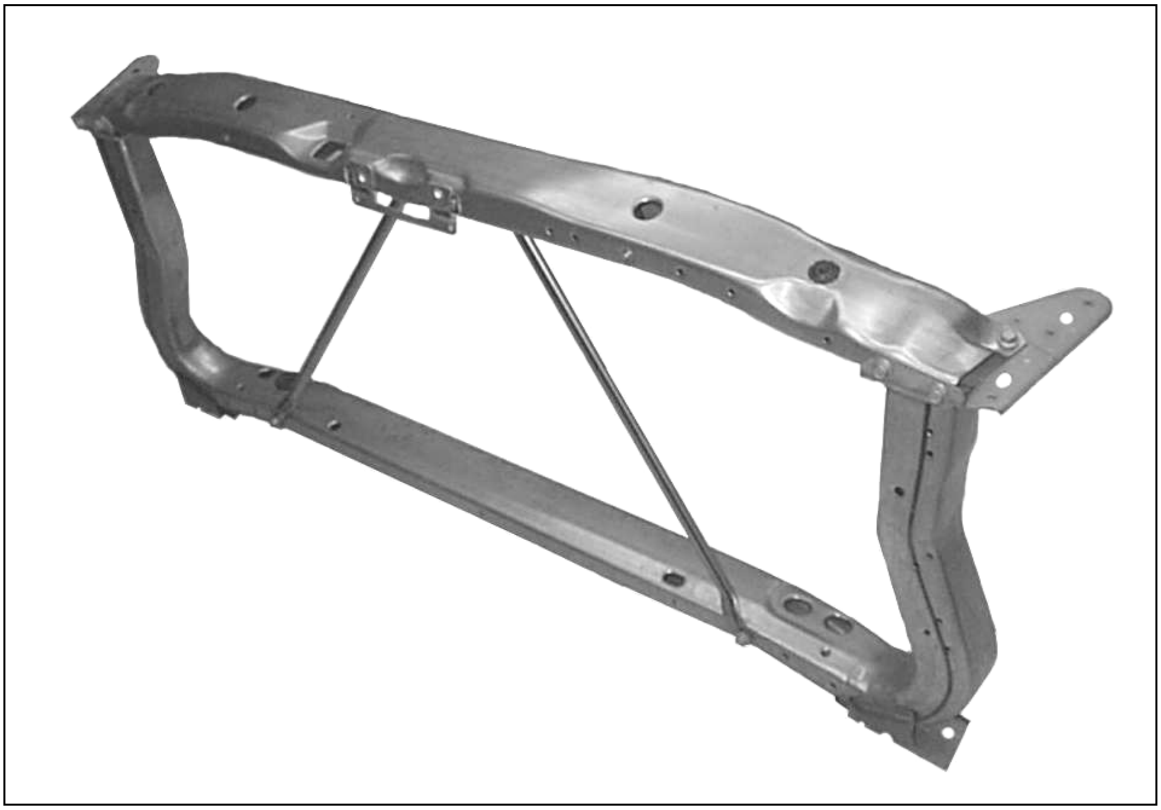

Figure 9 – Dodge Ram Pickup Radiator Closure Assembly

Other noteworthy design features include the use of galvanneal steel tube for the upper and lower hydroform members and the introduction of hexagon rivnut inserts. The radiator closure assembly makes extensive use of self-threading fasteners (37 in total) for the attachment of fenders, the V brace, intercooler, transmission cooler, and numerous sensors. To date over 2.0 million assemblies have been produced for use in the Dodge Ram Pickup truck.

Opel 2900 Engine Cradle Tube

The Opel Vectra is equipped with an engine cradle assembly, which also employs a tube formed using the Pressure Sequence Hydroforming process. The tube is produced by Krupp Camford in the U.K. for the European market using a single production line operating on a three shift basis. The cradle is also formed using High Strength Low Alloy steel tube and has twenty two holes pierced during hydroforming, ranging in size from 6 mm to 38 mm.

Figure 10 – Opel 2900 Engine Cradle Assembly

Dodge Dakota / Durango Radiator Closure Assembly

Immediately after the successful launch of the full size Dodge Ram pickup truck Chrysler began work on the new Dodge Dakota mid size truck. Replacing the conventional stamped and welded closure with one using hydroformed tubes resulted in 28% fewer parts and 24% less weight. These improvements are all the more significant by the fact that the new closure includes the ability to remove the upper tie bar for improved service access.

Although the hydroformed closure weighed 24% less, it provided between 40 and 150% better stiffness as compared to the original stamped design. The improved structural efficiency provided by the hydroformed tubes allowed for improved packaging which resulted in a 40% improvement in cooling airflow area.

Continuing efforts to further improve cooling capacity and simplify vehicle build have lead to the planned introduction of a modular cooling package for the 2000 model year. These trucks will utilize a single preassembled cooling package that include the radiator required for the chosen engine, any secondary coolers such as transmission oil, engine oil, or power steering fluid, and the air conditioning condenser.

The modular cooling package is designed to be set in front of the hydroformed closure assembly and then pivoted back in to position. For this to take place a new radiator mounting arrangement had to be devised.

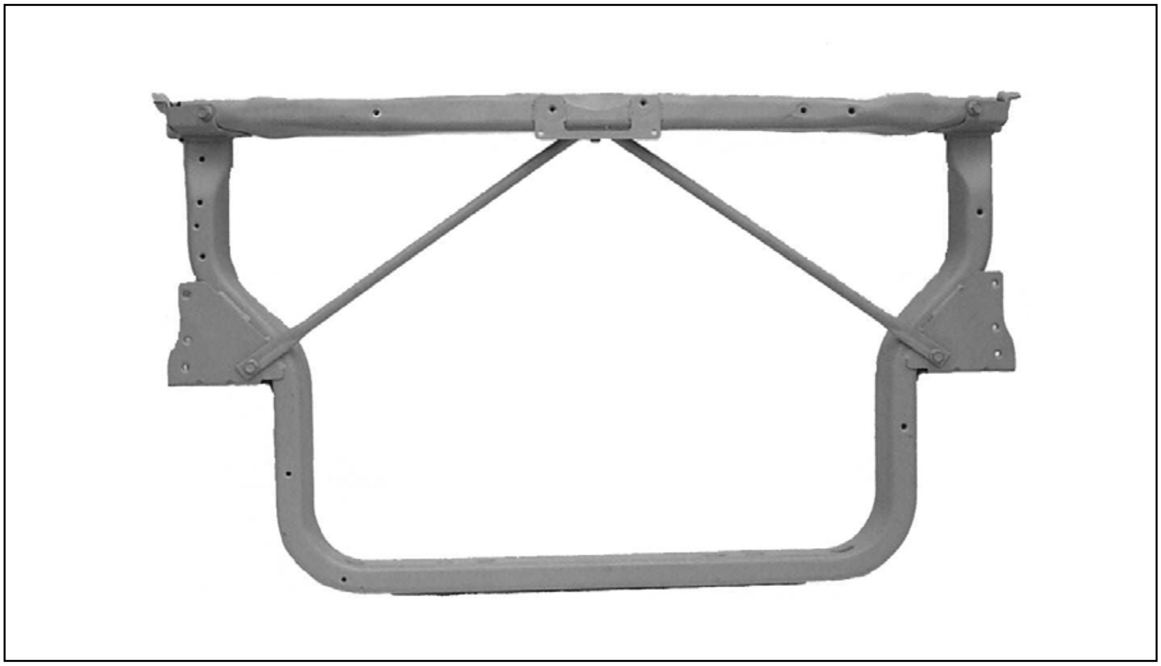

Figure 10 - Dodge Dakota/Durango Radiator Closure 1995 thru 1999

The proposed mounting arrangement for the modular package required mig welding four new stamping the existing hydroformed lower tube (see figure 11). Adding these additional components would have added significantly to the piece cost of the assembly as well as required a large investment in tools for stamping and welding. The additional components also resulted in the assembly being no longer compatible with the earlier versions of the assembly. This would result in increased complexity tracking and maintaining the required number of service parts for all models of trucks.

During the early prototype phase is was recognized by the team (OEM designer, Cooling Supplier, VF Project team) that every effort had to be made to reduce the cost impact of the change and develop a revised mounting design that would be compatible with the current cooling package. The team determined that if the current lower mounting slot in the hydroformed tube was enlarged and formed further into the bend, the lower cooling package mounts could be modified to mount directly to the tube. This would eliminate the two lower brackets and all their associated welds.

The only roadblock to introducing this was that no one had ever formed a large extruded slot on the inside of a bend before. Because of the risk involved with such a design, particularly since the change had to be done to a production part on the run, it was decided that the prototype tool be brought out of mothballs and modified with the desired hole. This decision provided an opportunity to debug the punch and validate the mounting arrangement in a production representative manor without risking current production.

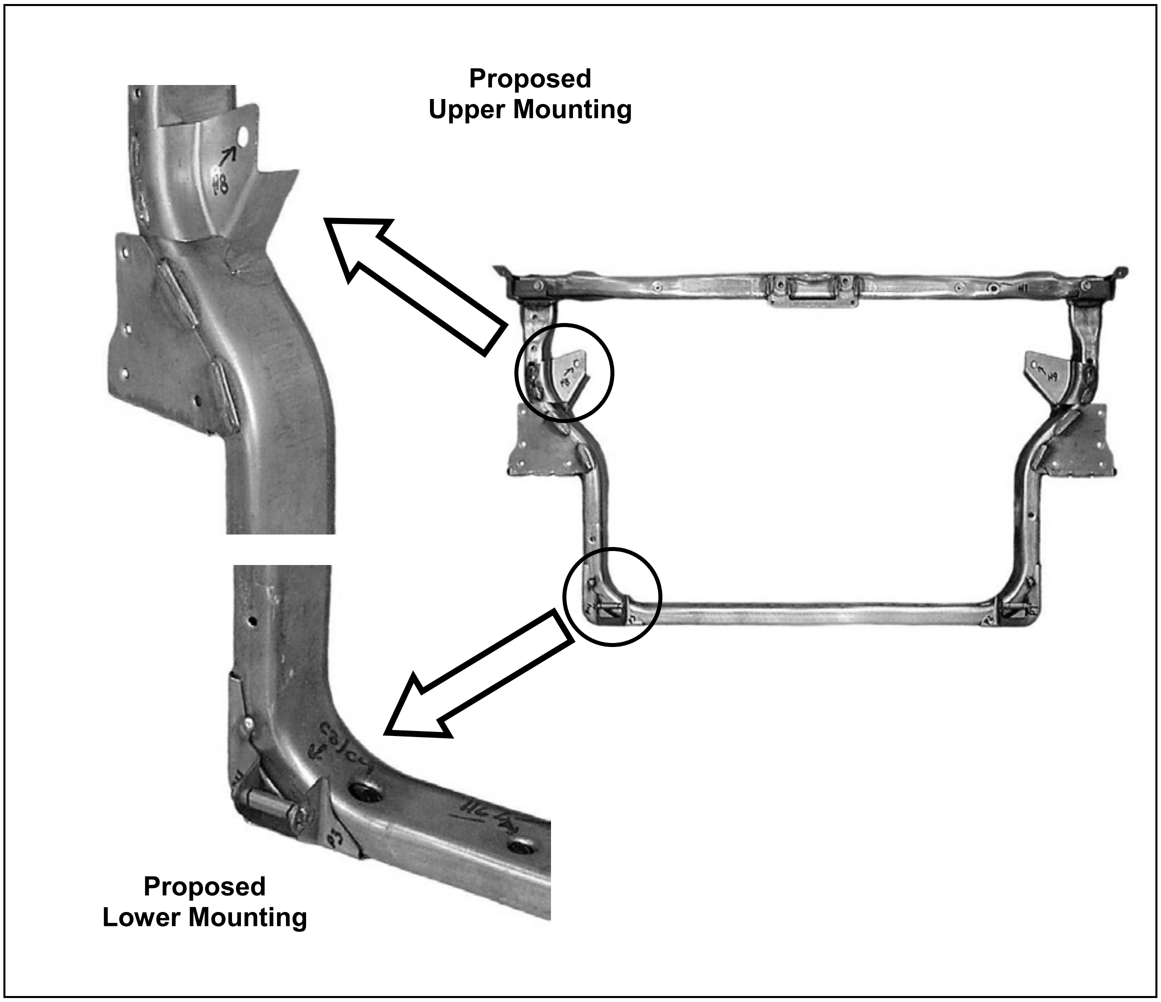

Figure 11 – Proposed Modular Cooling Package Mounting Arrangement

With the lower two brackets all but eliminated the attention of the group was turned to the upper mounting points. The original cooling package mounted at the top of the assembly using two rubber isolators bolted into the back of the upper hydroformed tube. Since the new modular cooling package mounts in front of the hydroform structure these mounts would no longer be accessible. Instead of using the proposed stamped brackets to form the upper mounts, the cooling module was revised to pickup on the front of the upper hydroformed tube. The brackets could then be replaced by adding two new hexagon holes with threaded inserts to the front of the upper hydroformed tube.

After the viability of forming the required hole was proven the entire concept was prototyped and tested. The revised design not only saved the cost of the proposed additional brackets but ultimately resulted in a reduction in the cost of each assembly. The final result was a cost saving of over $3.0 million and the new design enabled the changes to be introduced as a running change thus minimizing the interruption to production.

Jeep Grand Cherokee Lower Radiator Closure

The release of the redesigned Jeep Grand Cherokee saw the third introduction of a hydroformed Radiator Closure for DaimlerChrysler. The use of a hydroformed closure helped in meeting the platform goals of reducing weight and increasing body stiffness. Overall the new closure saved 5 lbs while helping the designers meet their targets for improved body stiffness. Piece cost was also reduced by over 15% from the previous models and the number of parts the assembly plant had to manage was reduced by 6. The new hydroformed assembly which is welded into the body in white structure, sets the width of the front fenders and frame rails.

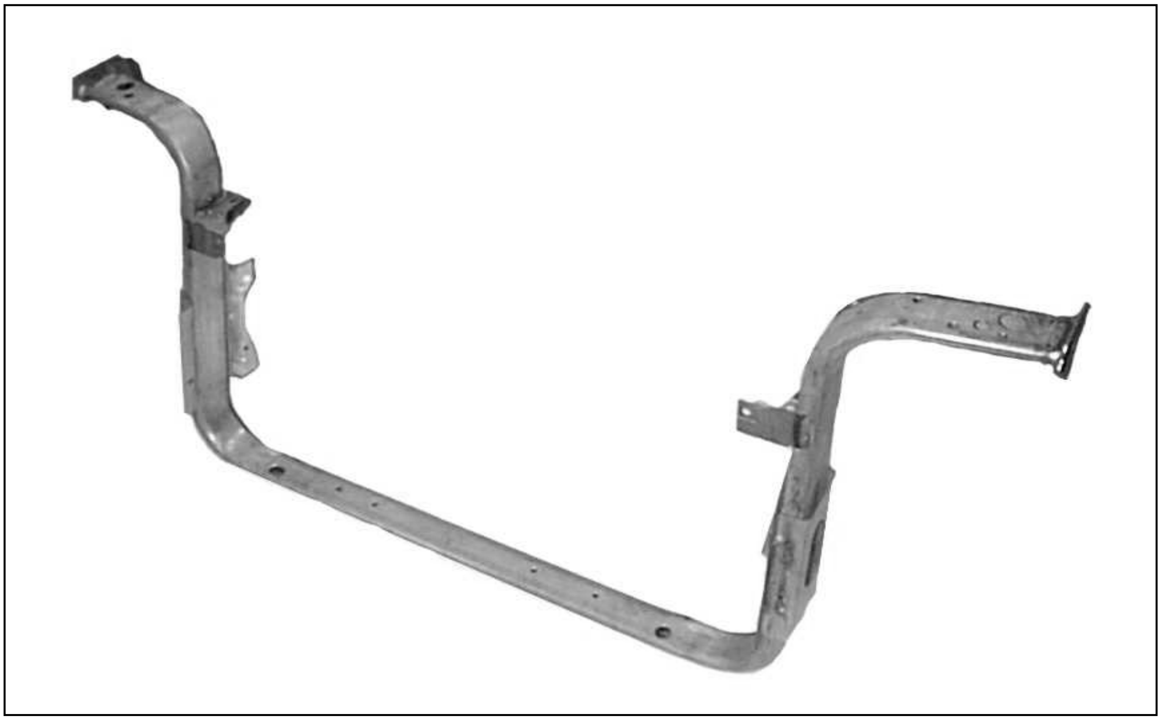

Figure 12 – Jeep Grand Cherokee Lower Radiator Closure Assembly

Dodge Neon Instrument Panel Beam

The redesigned 2000 Model Year Dodge Neon will utilize a hydroformed instrument panel beam. This support runs from the passenger side of the vehicle and connects to a magnesium casting that supports the instrument cluster area. The switch to a hydroformed tube from the previous version's bent tube was done in an effort to improve dimensional stability and stiffness.

The design flexibility of PSH allowed for the use a 3T outside corner radius which allowed for the maximum size of tube cross section area to be packaged into a very restrictive environment. Dimensional stability is further improved as the hydroformed tube allows for bolting the detail brackets to the tube rather than welding them, eliminating distortion of the final assembly due to the heat of welding.

As the part length is small it was decided to form two of the Left Hand Drive versions at a time, this results in forming a total of 64 holes per hit with a part being made in less than 11 seconds. As the Right Hand Drive version is produced in much smaller numbers they are produced one at a time. Another feature of note is the use of a large rectangular hole for the primary part datum. For reasons of access this hole requires an extruded clearance hole directly across from it on the opposite side of the cross section.

The cross section is narrow in this area of the tube and does not allow adequate room to punch the holes and leave the slugs attached inside the tube as is normally the case. Forming the holes outside of the hydroform tool would have added substantially to the processing costs and tooling. Instead the holes are punched during hydroforming, the slugs are captured, and then flushed out all prior to the part being released from the die.

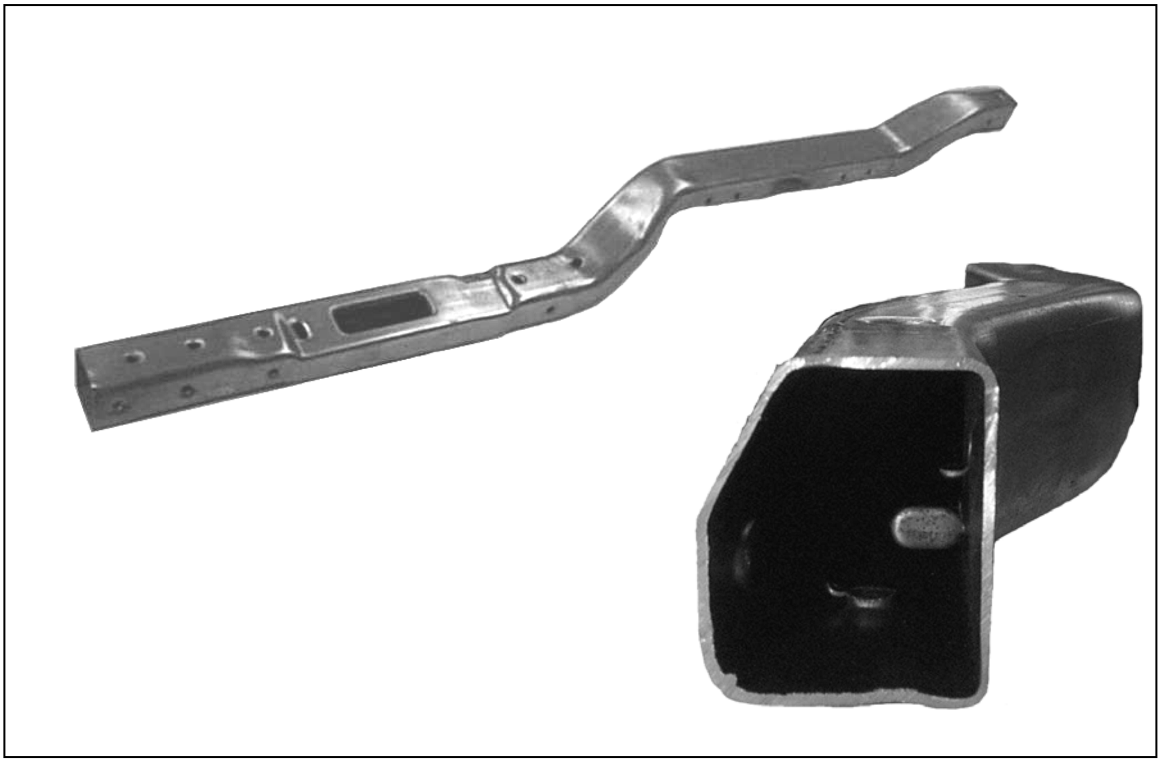

Figure 13 – Dodge Neon Hydroformed Instrument Panel Beam

SUMMARY

While hydroforming is new to the metal forming scene, it has quickly gained acceptance as a viable alternative to assembled stampings. After only 8 years hydroforming is no longer being used as a substitute for stampings, many new vehicle platform designs are calling for the use of hydroformed components as the primary design option. Taking advantage of all the flexibility that hydroforming has to offer requires input form all parties involved in vehicle design and build. When this simple rule is followed, the results speak for themselves.