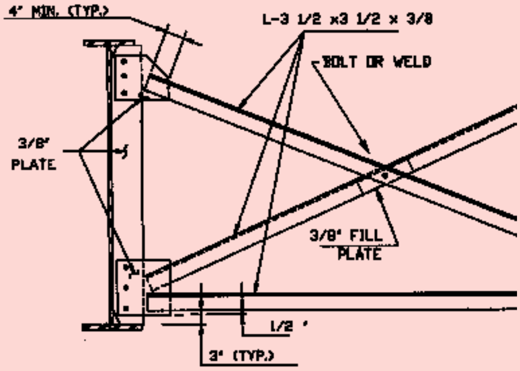

BRIDGE CROSSINGS

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Practical Information For The Bridge Industry

High Performance Steel: Design and Cost Comparisons

By Michael G. Barker and Steven D. Schrage

The introduction of High Performance Steel (HPS) for bridges has come at a rapid pace. While the unique material properties of HPS (such as higher yield strength, improved weldability, greater levels of toughness, and non-corrosive weathering resistance) make it an attractive material for bridge design, these features come at a premium price. As a result, the benefits realized by weight savings and reduced fabrication costs may be offset by the increased material costs.

HPS Properties and Characteristics

HPS can be generally defined by the following criteria:

1. Yield strength between 485 MPa (70 ksi) and 827 MPa (120 ksi).
2. Low carbon and carbon equivalent for weldability and ease of fabrication.
3. High levels of fracture toughness.
4. Adequate elongation and yield to tensile strength ratio for ductility.
5. Corrosion resistance superior to weathering steels currently used in highway bridges.

High performance steel's high strength provides the greatest potential economic benefit toward its use. The increased weldability, fracture resistance, and ductility it possesses are also superior to conventional steels of similar strength. These qualities lead to greater ease of fabrication and significantly lower cost, both short-term and long-term, allowing for a more practical higher strength steel. One of the successful high performance steels developed through research, HPS 485W (HPS 70W) was accepted by the American Society for Testing and Materials in 1998 and has been incorporated into their A709/A709M standard.

A present disadvantage is that HPS 485W (HPS 70W) is currently a quenched and tempered material. This limits the plate lengths that can be rolled to about 15000 mm (50 ft). Because of this, additional butt splices are often required to obtain the desired lengths commonly found in bridges. At the time of this writing, current research conducted by producers indicates that an as-rolled HPS 485W (HPS 70W) will be successfully achieved, eliminating the need for such plate length limitations. It is anticipated that this change may result in saving as much as half of the increased costs for HPS 485W (HPS 70W) over grade 345W (50W).

Bridge Design Alternatives

As part of a recent master's thesis project, six alternative designs were developed for a particular bridge site. The designs varied the number of girder lines and steel material. The designs followed the AASHTO Standard Specifications (16th ed) Load Factor method. Three homogeneous HPS 485W (HPS 70W) designs were compared to two 345W (50W) designs. HPS 485W (HPS 70W) has a yield strength of 485 Mpa (70 ksi) and 345W (50W) has a 345 Mpa (50 ksi) yield strength. A hybrid 345W/HPS 485W (50W/HPS 70W) design was also explored. In keeping with current trends for design optimization, all designs would use 345W (50W) steel for all stiffeners, diaphragms, and splice connection plates.

Fabrication and material costs were determined for all six design alternatives. Although the homogeneous HPS design alternatives demonstrated significant steel weight savings, the additional cost of the HPS material resulted in either no total cost savings or even an increased cost. However, the hybrid design clearly showed the potential benefits of HPS in bridges. Not only was there a weight savings, there was a considerable cost savings.

Certain factors were desired for the bridge site that would be used to create the design alternatives. Some of the desired traits included a new, continuous, multi-span slab-on-steel-girder bridge of significant size. With the cooperation of the Missouri Department of Transportation (MoDOT), a symmetrical 46630 mm (153 ft) two-span, continuous bridge with a 24° skew was selected. The bridge is to carry four lanes of traffic with shoulders over a U.S. Highway. Its roadway width is 30730 mm (68 ft) with a total width of 21540 mm (70 ft 8 in). The bridge falls into Fatigue Category II. The MoDOT 345W (50W) design calls for 9 girders spaced at 2440 mm (8 ft). Precast concrete deck panels provide the formwork onto which the remaining thickness of the slab is cast.

In creating all of the designs alternatives, a similar design procedure was followed. With certain bridge characteristics held constant such as span length, skew, and roadway width, three girder spacing geometries were examined. These included the original 9 girders at 2440 mm (8 ft) spacing, 8 girders at 2820 mm (9 ft 3 in) spacing, and 7 girders at 3250 mm (10 ft 8 in) spacing. This allows a direct comparison of steel weight and costs. The AASHTO Load Factor Design method was used.

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Each bridge was first designed by hand to obtain a preliminary design. These preliminary designs were then used to optimize and finalize each design using the bridge design software SIMON Version 8.1. All aspects of the final designs were completed using SIMON with the exceptions of the field splices, diaphragms, and shear connectors. These were all designed by hand. Whenever possible, the transverse stiffeners were used to frame the cross diaphragms to minimize additional diaphragm connection plates.

In the following presentation of the designs, only the elevation views of the girders are presented. The transverse stiffeners shown on the figures are the stiffeners required for bearing and shear design capacity (additional diaphragm connection plates not shown). The composite stud details, splice details, diaphragms and stiffener sizes are not shown for clarity, although they have been independently designed and are included in the steel weights and costs. The field splice location (change of section) is constant for all of the designs.

9 Girder 345W(50W) Bridge

The MoDOT geometry for the selected bridge site specified 9 girders at an 2440 mm (8 ft) spacing. This geometry (and not the actual MoDOT design) will be used as a basis for the alternate design comparisons. Figure 1 illustrates the elevation of the girder. This design has a flexure capacity performance ratio of 0.99 (design moment/section capacity) at the negative moment pier region. The 1830 mm x 13 mm (72 in x 0.5 in) web has a web slenderness of 144, a practical choice for maintaining a stress capacity near the yield stress in the flanges for a 345 MPa (50 ksi) material. Six one-sided intermediate stiffeners are required per girder to meet the shear requirements. The live load deflection is L/1900. The total steel weight (including stiffeners, etc.) is 326.6 tonnes (360.1 tons).

9 Girder HPS Bridge

The first HPS design used the same 2440 mm (8 ft) spacing as the original MoDOT bridge. The design uses HPS 485W (HPS 70W) for all plate steel in the girders, but uses 345W (50W) steel for all stiffeners, diaphragms, and field splice connection plates. Figure 2 shows an elevation view for the 9 girder HPS bridge. The design has a flexure capacity performance ratio of 0.95 at the negative moment pier region. The 1625 mm x 13 mm (64 in x 0.5 in) web has a web slenderness of 128, a practical choice for maintaining a stress capacity near the yield stress in the flanges for a 485 MPa (70 ksi) material. The live load deflection is L/1350. The total steel weight is 277.8 tonnes (306.3 tons).

Clearly the weight of the steel decreases with the use of HPS. The girder is shallower, the flanges slightly smaller, and the live load deflection larger. There are also two less intermediate stiffeners required per girder.

8 Girder HPS Bridge

By removing a girder line and increasing the girder spacing to 2820 mm (9 ft 3 in), another HPS alternative was created. This design uses HPS 485W (HPS 70W) for all plate steel in the girders. Figure 3 shows an elevation view for the 8 girder HPS bridge. The design has a flexure capacity performance ratio of 0.99 at the negative moment pier region. To remove a girder line, the web depth increases 51 mm (2 in) compared to the 9 girder HPS design. The 8 girder HPS bridge requires only two intermediate stiffeners per girder. The live load deflection is L/1400. The total steel weight is 272.7 tonnes (300.6 tons).

The steel weight difference between the 9 girder and 8 girder HPS bridge designs is not significant. However, there will be considerable savings in having one less girder line (fabrication, erection and number of stiffeners and diaphragms).

7 Girder HPS Bridge

Removing another girder line and increasing the girder spacing to 3250 mm (10 ft 8 in) creates a third HPS bridge. This design also uses HPS 485W (HPS 70W) for all plate steel in the girders. Figure 4 shows an elevation view for the 7 girder HPS bridge. The design has a flexure capacity performance ratio of 1.00 at the negative moment pier region. To remove two girder lines from the 9 girder HPS design, the web depth increases 203 mm (8 in). The 7 girder HPS bridge requires only two intermediate stiffeners per girder. The live load deflection is L/1650. The total steel weight is 270.6 tonnes (298.3 tons).

Again the steel weight differences between the three HPS bridge designs is not significant. However, for the 7 girder design, the removal of two girder lines and all the associated diaphragms and intermediate stiffeners will result in considerable cost savings.

7 Girder 345W(50W) Bridge

If removing girder lines and diaphragms reduce the weight and/or cost of a bridge, then to fully compare the 345W (50W) and HPS 485W (HPS 70W) materials it is necessary to also include a 7 girder 345W (50W) bridge design. Figure 5 shows the elevation view for the 7 girder 345W(50W) steel bridge. The design has a flexure capacity performance ratio of 0.99 at the negative moment pier region. To remove two girder lines from the 9 girder 345W(50W) design, the web depth increases 254 mm (10 in). It is also 254 mm (10 in) deeper than the 7 girder HPS girder. The 7 girder 345W(50W) bridge requires 10 intermediate stiffeners per girder, even two near the abutments. The live load deflection is L/2350. The total steel weight is 310.5 tonnes (342.3 tons).

There is only a slight weight savings over the 9 girder 345W(50W) bridge design, but there will also be the savings from removing the girder lines and diaphragms. However, the 7 girder 345W(50W) design will require many more intermediate stiffeners. This is especially true when compared to the 7 girder HPS design. The 7 girder HPS design also saves considerable steel weight over the 7 girder 345W(50W) design.

7 Girder Hybrid Bridge

From the above design examples, it is clear that the 7 girder designs will be more economical than the 9 girder designs. The 7 girder 345W(50W) design will have less material, fabrication and erection costs than the 9 girder 345W(50W) design and likewise for the HPS 485W (HPS 70W) material. Therefore, the final design example will examine the case of a hybrid 7 girder bridge. The object is to take advantage of HPS where demand is highest and use conventional (and less expensive) 345W (50W) steel where the demand is lower. Using the 7 girder spacing of 3250 mm (10 ft 8 in), a design was created that consisted of using 345W (50W) steel for all web plate material. In addition, grade 345W (50W) steel was used in the top flange in the positive moment region where the section is composite. For the highly stressed regions, the bottom flange in the positive moment region and both flanges in the negative moment region, HPS 485W (HPS 70W) was used. Again, grade 345W (50W) steel was used for all stiffeners, diaphragms, and field splice connection plates.

Figure 6 shows an elevation view for the 7 girder hybrid steel bridge (shaded area represents the HPS material). The design has a flexure capacity performance ratio of 1.00 at the negative moment pier region. The 1830 mm (72 in) web size is the same as the 7 girder HPS girder, although it is a different material and there are two additional intermediate stiffeners required per girder. The live load deflection is L/1750. The total steel weight is 276.7 tonnes (305.0 tons).

As expected, the steel weight is between the 7 girder 345W(50W) and HPS bridge designs. The same is true for the number of intermediate stiffeners.

Design Comparisons

Having explored the six design alternatives, a comparison is presented in Table 1. In Table 1, the number of diaphragms includes both intermediate as well as end diaphragms. The number of intermediate stiffeners includes the number of additional stiffeners required above those required to attach the diaphragms for the total bridge. Finally, the weight of the stiffeners, splice plates, and diaphragms are included in the 345W (50W) weight quantities. Table 2 illustrates the alternative design weight savings from that of the 9 girder 345W(50W) design and the 7 girder 345W(50W) design.

From the tables, several general trends become apparent. As girder spacing increases (girder lines decrease), total steel weight decreas-

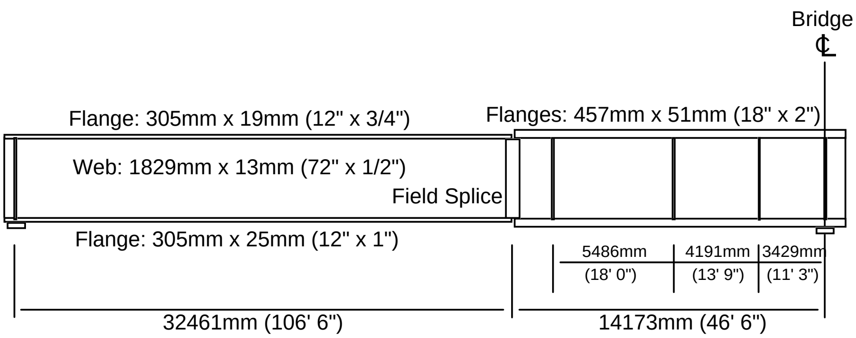

Figure 1: Elevation View of 9 Girder 345W (50W) Steel Bridge

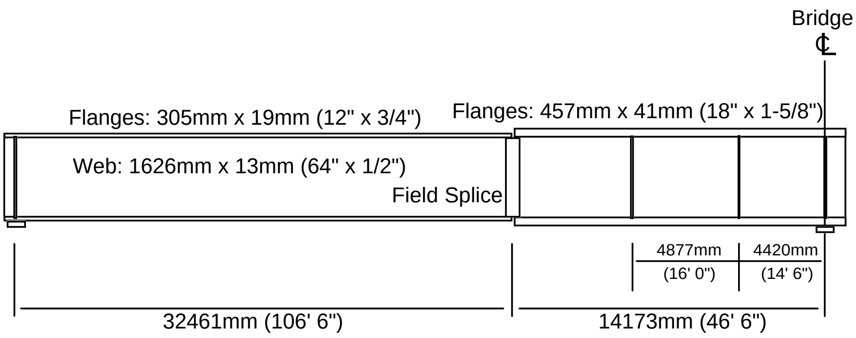

Figure 2: Elevation View of 9 Girder HPS Steel Bridge

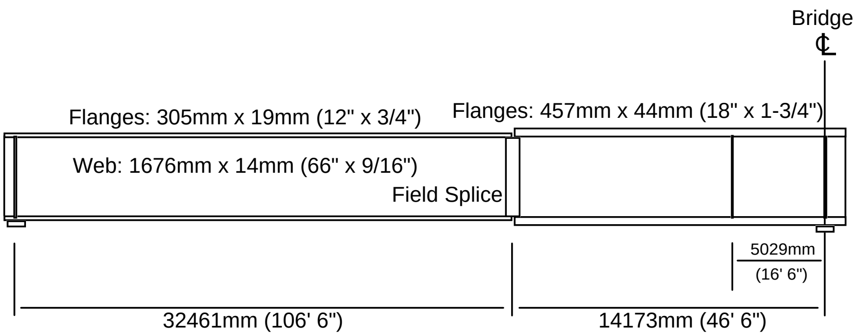

Figure 3: Elevation View of 8 Girder HPS Steel Bridge

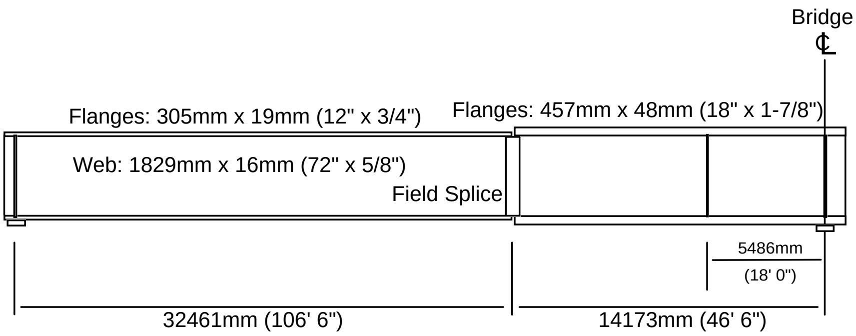

Figure 4: Elevation View of 7 Girder HPS Steel Bridge

es. While individual girders increase in weight, the total steel weight of all girders decreases. In addition to lower total weight, another advantage is that fewer girder lines require fewer splices, fewer stiffeners, and fewer diaphragms for the total bridge. There are also fewer girders to be fabricated, handled, shipped, and erected.

As anticipated, HPS bridges tend to be lighter than those constructed of conventional steel. Another observable trend is that, by using HPS webs, significantly fewer intermediate stiffeners are required above those required for the diaphragms due to the high shear capacity of these webs.

Thus, with the weight savings and number of stiffeners and diaphragms, HPS 485W (HPS 70W) steel bridges seem promising. However, HPS 485W (HPS 70W) currently costs significantly more than 345W (50W) material. To examine the potential benefit of HPS 485W (HPS 70W), the total costs associated with each design alternative need to be compared.

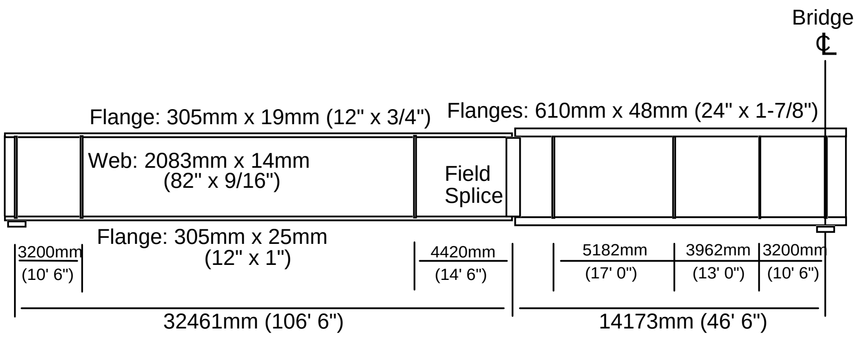

Figure 5: Elevation View of 7 Girder 345W (50W) Steel Bridge

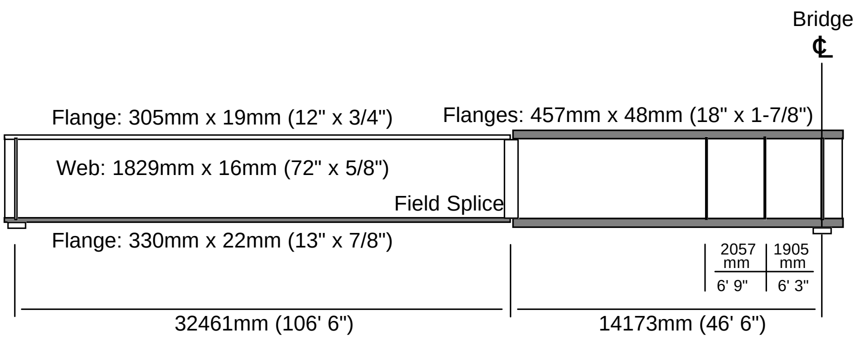

Figure 6 Elevation View of 7 Girder Hybrid Steel Bridge

Table 1: Bridge Design Alternatives Summary

Design Alternative	Girder Lines	Total Diaphragms	Additional Stiffeners	Steel Weight tonnes (tons) 45W(50W)	HPS	Total
9 Girder 345W(50W)	9	120	38	326.6 (360.1)	0 (0)	326.6 (360.1)
7 Girder 345W(50W)	7	90	46	310.5 (342.3)	0 (0)	310.5 (342.3)
9 Girder HPS	9	120	4	13.2 (14.6)	264.6 (291.7)	277.8 (306.3)
8 Girder HPS	8	105	2	13.0 (14.3)	259.7 (286.3)	272.7 (300.6)
7 Girder HPS	7	90	2	12.9 (14.2)	257.7 (284.1)	270.6 (298.3)
7 Girder Hybrid	7	90	28	182.7 (201.4)	94.0 (103.6)	276.7 (305.0)

Cost Comparisons

Bridge owners are primarily interested in the final cost. Therefore, the six designs presented were sent to a reputable steel fabricator for material, fabrication, shipping and erection costs. The costs received from the fabricator were separated into total fabrication costs and material, transportation and erection (MTE) costs as shown in Table 3 for the six design alternatives. Table 3 uses current material costs, as given by the fabricator, for HPS 485W (HPS 70W) of $1259/tonne ($1142/ton) for material, transportation and erection while 345W (50W) is only $928/tonne ($842/ton). This represents an additional 35.6% cost for HPS 485W (HPS 70W).

However, with new research and an as-rolled HPS material, it is hoped to reduce the price of HPS 485W (HPS 70W) to around 15% above that for 345W (50W) material. Anticipating the successful development of a less-expensive HPS 485W (HPS 70W), Table 4 presents the costs using $1067/tonne ($968/ton) for HPS 485W (HPS 70W). The fabrication costs have not been changed, even though they would be expected to decrease with such aspects such as longer plate lengths resulting in fewer butt welds.

From the costs, it is apparent that the 7 girder hybrid design has the lowest cost. Savings of 18.6% and 11% using current costs and 21.9% and 14.6% using projected costs are predicted compared to the 9 girder and 7 girder 345W(50W) designs, respectively, as shown in Table 5. The use of HPS only in the highly stressed areas and 345W (50W) for the remaining steel is an efficient and economical combination.

The homogeneous HPS designs did not fare as well. Although they save considerable steel weight, the additional cost associated with the HPS material overcomes most or all of the lesser weight benefits. For current HPS material costs, all the homogeneous HPS designs cost more than the 7 girder 345W(50W) design. The only case of a savings is 0.4% for the 7 girder HPS design compared to the 9 girder 345W(50W) design. For the projected costs, the analysis is slightly better, but, clearly, the 7 girder hybrid design is the only alternative that definitely demonstrates significant cost savings. Homogeneous HPS girders use the more expensive material inefficiently in low stress regions.

Conclusions

With the potential benefits of High Performance Steel (HPS) for steel bridges, an investigation into the economy of such bridges was conducted in an effort to evaluate the new construction material. The purpose of this paper was to demonstrate the benefits of HPS 485W (HPS 70W) girder bridges compared to conventional 345W (50W) steel girder bridges.

Six alternative designs were developed for a particular bridge site. The designs varied in number of girder lines and steel material. Three homogeneous HPS designs were compared to two 345W (50W) designs. A hybrid 345W/HPS 485W (50W/HPS 70W) design was also explored.

Fabrication and material costs were determined for all six design alternatives. Although the HPS design alternatives demonstrated significant steel weight savings, the additional cost of the HPS material resulted in no total cost savings or even an increased cost. However, the hybrid design clearly showed the potential benefits of HPS in bridges. Not only was there a weight savings, there was also a considerable cost savings.

Several common trends observed in this study yield the following conclusions. A bridge designer can use these conclusions to develop recommendations for creating economical steel bridge designs:

1. Greater girder spacings tend to produce less expensive bridges due to fewer girder lines for fabrication and erection as well as fewer diaphragms, stiffeners and a lighter total steel weight.
2. Simplified designs can reduce fabrication costs. Often, the least weight design is not the most economical. In general, designs should include as few stiffeners and flange transitions as practical.
3. Using HPS allows for designs that have less steel weight than conventional steel designs.
4. Designing homogeneous HPS girders allow for lighter sections, but may not lower total costs because of the increase in material and fabrication costs for HPS.
5. The higher costs associated with HPS can lead to more expensive designs.
6. Hybrid designs seem to be more economical than 345W (50W) or homogeneous HPS 485W (HPS 70W) designs. Hybrid designs using HPS in the highly stressed flanges and conventional steel everywhere else are highly efficient.
7. As-rolled HPS 485W (HPS 70W), lower material costs, and fabricators' continued experience working with HPS will have a significant impact on the use and economy of HPS bridge designs.

Table 2: Bridge Weight Savings

Design Alternative	% Weight Savings over 9 Girder 345W(50W)	% Weight Savings over 7 Girder 345W(50W)
9 Girder 345W(50W)	Base	-5.2%
7 Girder 345W(50W)	4.9%	Base
9 Girder HPS	14.9%	10.5%
8 Girder HPS	16.5%	12.2%
7 Girder HPS	17.1%	12.8%
7 Girder Hybrid	15.3%	10.9%

Table 3: Cost Analysis Using Current HPS Costs*

Design Alternative	Fabrication Costs ($)	MTE Costs ($)	Total Costs ($)
9 Girder 345W(50W)	249,119	303,170	552,290
7 Girder 345W(50W)	216,941	288,191	505,132
9 Girder HPS	260,607	345,386	605,993
8 Girder HPS	227,837	339,035	566,872
7 Girder HPS	213,595	336,441	550,036
7 Girder Hybrid	161,720	287,871	449,591

Table 4: Cost Analysis Using Projected HPS Costs*

Design Alternative	Fabrication Costs ($)	MTE Costs ($)	Total Costs ($)
9 Girder 345W(50W)	249,119	303,170	552,290
7 Girder 345W(50W)	216,941	288,191	505,132
9 Girder HPS	260,607	294,632	555,239
8 Girder HPS	227,837	289,215	517,052
7 Girder HPS	213,595	287,003	500,598
7 Girder Hybrid	161,720	269,841	431,561

Table 5: Summary of Cost Savings*

Design Alternative	Current HPS Mat. Costs		Projected HPS Mat. Costs	
	% Cost Savings over 9 Girder 345W(50W)	% Cost Savings over 7 Girder 345W(50W)	%Cost Savings over 9 Girder 345W(50W)	%Cost Savings ove 7 Girder 345W(50W
9 Girder 345W(50W)	Base	-9.3%	Base	-9.3%
7 Girder 345W(50W)	8.5%	Base	8.5%	Base
9 Girder HPS	-9.7%	-20.0%	-0.5%	-9.9%
8 Girder HPS	-2.6%	-12.2%	6.4%	-2.4%
7 Girder HPS	0.4%	-8.9%	9.4%	0.9%
7 Girder Hybrid	18.6%	11.0%	21.9%	14.6%

**** Please note: The cost data The cost data is as provided by fabricators at th time of the study.***

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