J. Cost Assessment of Emerging Magnesium Sheet Production Methods

Principal Investigator: Darrell R. Herling
Pacific Northwest National Laboratory
P.O. Box 999, MS: K2-03, Richland, WA 99352
Ph: (509) 375-6905, Fax: (509) 375-4448, E-Mail: darrell.herling@pnl.gov

Technology Area Development Manager: Joseph A. Carpenter
(202) 586-1022; fax: (202) 586-1600; e-mail: joseph.carpenter@ee.doe.gov
Field Technical Manager: Philip S. Sklad
(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

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Objective

Magnesium has the highest specific stiffness and second highest specific strength of all structural metals. Because of this, there is an increasing global interest in using magnesium for structural components. A number of research activities are under way to develop approaches for producing magnesium sheet at the volume and cost levels demanded by automotive applications. The economics associated with some of these emerging yet promising technologies are unclear. The United States Council for Automotive Research (USCAR), in an effort to better understand the cost factors and potential for low-cost production, commissioned a study to develop a technical cost model on magnesium sheet production. The Aluminum Consultants Group, in conjunction with Pacific Northwest National Laboratory, prepared a technical cost model for magnesium sheet production alternatives.

Approach

In developing the cost model, options for producing magnesium sheet were identified and processing details studied. The model focuses on the two most commercially prominent continuous-casting processes, twin-belt casting and twin-roll casting. The design and data used in the model are largely based on information and experience with aluminum continuous casting, with anticipated modifications required for magnesium sheet production. Supplemental information specific to magnesium continuous casting was obtained from the literature and solicited directly from organizations involved in each of the processes. The model focuses on three primary elements: metal cost; casting process cost; and sheet rolling cost.

Accomplishments

For the continuous-cast magnesium sheet model, two "base cases" were developed to provide a starting point for subsequent sensitivity analyses. These two base cases used the same inputs for the metal cost and rolling cost elements, with a difference in the casting costs. The projected production costs for twin- roll and twin-belt casting of 1.5-mm-thick magnesium sheet are $1.97 per pound and $2.43 per pound, respectively. This compares to an industry-quoted price (including profit and overhead costs) of $4.50 per pound for magnesium sheet currently produced by conventional ingot metallurgy methods.

Future Direction

Though production costs for continuous casting are estimated to be significantly less than for conventional methods, to meet targeted performance properties, much still needs to be learned about processes. An increased understanding is needed of how alloy composition and process conditions produce the resulting microstructures. Modeling of continuous-casting processes has been a focus of research and can be applied to magnesium alloys along with critical experiments. In addition, future research must establish the envelope of continuous-casting capabilities for magnesium, addressing aspects such as strip width, as-cast strip thickness, and casting rate and their effects on important issues such as segregation, cast grain structure, and surface quality. Underlying all of these studies is a better understanding of the relationship of alloy microstructure and sheet formability as well as other mechanical properties such as corrosion resistance, all of which are necessary for automotive applications.

Introduction

The growth of interest in and use of magnesium in automotive applications has been primarily in the area of cast components, similar to aluminum in the past. Because magnesium has the highest specific stiffness and second highest specific strength of any metal, there is an increasing global interest in extending its potential weight-saving opportunities into auto body and structural components. This would necessitate the use of formable magnesium sheet. Currently, little infrastructure exists for the production of magnesium sheets because its application in highly specialized uses such as photoengraving sheet is limited. Because of this limited production capacity and the inherent difficulties in thermomechanical processing of magnesium due to its hexagonal close-packed crystal structure, magnesium sheet prices are presently well above the levels that would be considered acceptable for automotive applications.

Worldwide activities are underway to develop approaches for producing magnesium sheet at the volume and cost levels demanded by automotive application. These approaches include efforts to better understand and improve the conventional processing of magnesium sheet via ingot-casting, hot-rolling, and cold-rolling methods, as well as some alternatives such as nearer-net-shape continuous-casting type processes.

The Materials Technical Team of the United States Council for Automotive Research (USCAR) sought to better understand the cost drivers of magnesium sheet production and the potential impact that alternative processing approaches could have. The Aluminum Consultants Group, in conjunction with the Pacific Northwest National Laboratory, prepared a technical cost model for magnesium sheet production alternatives. The results of this effort are the substance of this report. Specifically, the three objectives of this study were to:

- Provide a framework for understanding the primary cost elements for the production of magnesium sheet by conventional as well as alternative processing methods.
- Evaluate the effects of a range of potential values for key variables to identify the key cost drivers.
- Suggest areas of focus for research and development (R&D) activities based on these results.

Magnesium Sheet Cost Model

To begin to understand the main cost drivers and potential benefits of alternative processing routes for production of magnesium sheet, a technical cost model was developed. The model focuses only on the two most commercially prominent continuous casting processes, twin-belt casting and twin-roll casting, and does not directly address the technical cost elements of conventional magnesium sheet processing methods.

The design and data used in the model are largely based on information and experience with aluminum continuous casting, with anticipated modifications required for magnesium sheet production. The model focuses on three primary elements, specifically:

- Metal cost
- Casting process cost
- Sheet rolling cost.

A few caveats about the modeling approach are needed. First, this model is intended for scoping analysis only and clearly is not intended to be a rigorous modeling of production cost. Second, the model does not include profit considerations.

Within the framework of the model, the selection of input values to produce useful outputs is the next critical step. For the Continuous Cast Magnesium Sheet Model, two “base cases” were developed to provide a starting point for subsequent sensitivity analyses. These two base cases used the same inputs for the Metal Cost and Rolling Cost components with a difference in the Casting Cost section. Specifically, a base case was developed for each of the two continuous casting processes of interest, twin-roll casting and twin-belt casting. In this section, values used for the base cases and the rationale for their selection are provided. Also, the output for a total cost per pound for magnesium sheet using the base case assumptions is provided.

For the base case, a standard product and desired production volume were selected. The values used were 1.5-mm(0.40 in)-thick x 1-m(40 in)-wide sheet at a production volume of 10,000 tons per year (tpy). The sheet thickness and width are considered of interest for automotive body panels, while the production volume represents a roughly 10x increase over the current sheet production volume by conventional processing.

Metal Cost Inputs

The base metal price input for the base case, using AZ31 alloy, was set using the prices of the individual constituents (Mg, Al, and Zn) at the June 2005 American Metal Market free-market price in proportion to their concentration in the alloy. The resulting input price used was $1.47 per pound. The recycle component is calculated from the assumed rolling recovery; in the base case, it is 25%.

Melt loss is assumed to be on the higher end of that typical for aluminum, although no specific data were found for magnesium. A value of 5% melt loss is used in the base case.

Casting Cost Inputs

Some inputs were common for both the twin-roll and twin-belt casting cases. The as-cast strip width was selected to be 48 inches to result in a 40-inch-wide sheet, accounting for edge losses during rolling. Variable costs per hour were established at $200 for both processes.

Twin-Belt Casting

For twin-belt casting, base case values were used that reflected lower range values for aluminum processing, adjusted only for the density differences between magnesium and aluminum. Thus, a continuous-casting productivity value for the base case of 700 lb/hr-in was used, which is roughly 0.7 times the lower-range value for aluminum twin-belt casting. Using this productivity value and assuming 6,720 hours of production time per year, a casting capacity of roughly 112,000 tons was calculated, which is consistent with reported values for casting capacity in the literature (Hamer et al. 2002). Adjustments were made to the number of operating hours per year to produce the required casting output.

Based on information obtained from discussions with a supplier of twin-belt casting equipment[a], capital cost for a unit consisting of a caster and associated in-line rolling stands is approximately $80 million, resulting in a fixed cost per machine of 15% of that amount. Because the required casting output for this base case is roughly 10% of the machine capacity, the fixed cost per ton is significantly higher than if the machine were producing at full capacity.

Twin-Roll Casting

For twin-roll casting, a continuous-casting productivity of 45 lb/hr-in was used, again representing roughly 0.7 times the lower end of the aluminum range. Based on this productivity, one casting machine is not adequate to meet the casting output requirement, necessitating two machines in the base case.

Again, information from a supplier of twin-roll casters indicated that a casting unit costs $6 million[b], and the fixed cost per machine is calculated accordingly. Using the base case production target level, two casting machines are operated near capacity. Along with their lower overall capital cost, this results in a lower fixed cost per ton for the twin-roll casting base case than for the twin-belt casting case.

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[a] Peter Regan, Hazelett, personal communication with Gerald Cole, Lightweight Strategies LLC, February 2005.

[b] Chris Romanowski, FATA Hunter, personal communication with Gerald Cole, Lightweight Strategies LLC, February 2005.

Rolling Cost Inputs

For both base cases, an as-cast thickness prior to downstream rolling of 0.12 inches was selected, consistent with capabilities described in the literature for aluminum (Hamer et al. 2002, von Gal 2000). In twin-belt casting, this is actually not the true as-cast thickness but rather the as-cast thickness further reduced by the in-line rolling capability that is part of a twin-belt casting unit. In twin-roll casting, this is the true as-cast thickness. A reduction-per-pass value of 30% is used, which is in the mid-range of reports for warm rolling of magnesium in the literature (Liang and Cowley 2004, Park et al. 2004). A rolling cost/pass of $0.05 per pound was used based on information from discussions with suppliers[c]. It is somewhat higher than the cost for aluminum, recognizing in particular the need for heating prior to each pass. No specific assumptions were made regarding rolling speeds due to a lack of available data. Finally, a rolling recovery of 75% was selected for this base case.

Conclusions from Cost Modeling

Using the input values described above, the model was run to calculate the estimated cost for magnesium sheet produced by the twin-belt casting and twin-roll casting methods. Summary spreadsheets for the twin-belt cast and twin-roll cast base cases are provided in Tables 1 and 2, respectively. The results are tabulated in Table 3, and the percent of total cost for each element is shown in Figure 1. Estimated production cost for twin-belt and twin-roll continuous casting is $2.43 and $1.97 per pound, respectively.

For comparison, a price quote for the same sheet size and production volume was obtained from SCI, a subsidiary of Magnesium Electron Ltd., the producer of conventionally-rolled AZ31 sheet. The price quoted was $4.50 per pound. It is important to note that this is a price quote, including factors related to profit and capital recovery, while the model predictions are cost estimates.

Sensitivity Analyses

While the estimated cost values derived from the base-case assumptions are interesting and potentially useful alone, another purpose of creating the spreadsheet cost model is to allow assessment of the effects of changes in the values of input variables on the estimated cost with a goal of identifying the variables that are most sensitive. This information in turn can be used to determine the areas where further R&D would provide the most cost leverage. Four variables were the focus of sensitivity analyses based on their expected impact; specifically, metal price, annual sheet production volume, caster productivity, and rolling parameters of reduction per pass and rolling recovery. For each case, values of the variable of interest were changed while other base-case assumptions were held constant. The results for each analysis will be reviewed in turn.

Metal Price

Metal price can vary depending on the source of the alloy and market conditions. Two additional metal price values were examined besides the base-case assumption of $1.47 per pound. A value of $0.84 per pound was used as a lower bound assumption based on information that this is a typical price for AZ31 in Europe (AMM 2005). A higher value of $1.60 per pound was also examined based on historical data (Kramer 2004). Running the model with these variations results in the total cost per pound listed in Table 4. Because metal price is such a significant fraction of the total sheet cost, it is not surprising that changing the input metal price has a large effect on the estimated final sheet cost.

Annual Production Volume

While the production volume level of 10,000 tpy used in the base case is a significant increase over the volume of magnesium sheet now produced by conventional processing, it is still modest by automotive volume standards. Three higher values of annual production volume were analyzed, and the results are shown in Table 5.

Increasing annual production volume had the largest effect on the sheet cost produced by the twin-belt casting process, primarily through better utilization

[c] Chris Romanowski, FATA Hunter, personal communication with Gerald Cole, Lightweight Strategies LLC, February 2005.

Table 1. Base Case Results for Twin-Belt Casting

Base Case Twin-Belt Casting					
Metal Cost Input		**Casting Cost Input**		**Rolling Cost Input**	
Base metal price/lb	$1.47	Strip width (in)	48	As-cast thickness (in)	0.12
Recycle component (%)	25	Cont. casting productivity (lb/hr-in)	700	Final Thickness (in)	0.06
Melt loss (%)	5	Casting capacity/machine (tpy)	112896		
		Number of machines	1	Reduction per pass (%)	30
		Total casting capacity (tpy)	112896	Number of rolling passes	3
		Fixed cost/machine (per yr)	$12M	Rolling cost/pass	$0.05
		Fixed costs (per ton)	$900		
		Variable costs (per hr)	$200	Rolling recovery (%)	75
		Uptime (%)	80		
		Shifts per week	20		
		Weeks of operation	6		
		Operating hours per year	794		
Cost/finished/lb	$1.62	Cost/finished/lb	$0.61	Cost/lb	0.20
Total cost/lb					**$2.43**
		Casting output/(tpy)	13334	Annual production vol (tpy)	10000
		Under/over capacity (tpy)	99562		

Table 2. Base Case Results for Twin-Roll Casting

Base Case Twin-Roll Casting					
Metal Cost Input					
Base metal price/lb	$1.47	Strip width (in)	48	As-cast thickness (in)	0.12
Recycle component (%)	25	Cont. casting productivity (lb/hr-in)	45	Final Thickness (in)	0.06
Melt loss (%)	5	Casting capacity/machine (tpy)	7258		
		Number of machines	2	Reduction per pass (%)	30
		Total casting capacity (tpy)	14515	Number of rolling passes	3
		Fixed cost/machine (per yr)	$12M	Rolling cost/pass	$0.05
		Fixed costs (per ton)	$900,000		
		Variable costs (per hr)	$135	Rolling recovery (%)	75
		Uptime (%)	80		
		Shifts per week	21		
		Weeks of operation	46		
		Operating hours per year	6173		
Cost/finished/lb	$1.62	Cost/finished/lb	$0.15	Cost/lb	0.20
Total cost/lb					**$1.97**
		Casting output/(tpy)	13333	Annual production vol (tpy)	10000
		Under/over capacity (tpy)	1182		

Table 3. Results for Base Cases

Process	Metal Cost/Finished lb	Casting Cost/Finished lb	Rolling Cost/Finished lb	Total Cost/lb
Twin-Belt	$1.62	$0.61	$0.20	**$2.43**
Twin-Roll	$1.62	$0.15	$0.20	**$1.97**

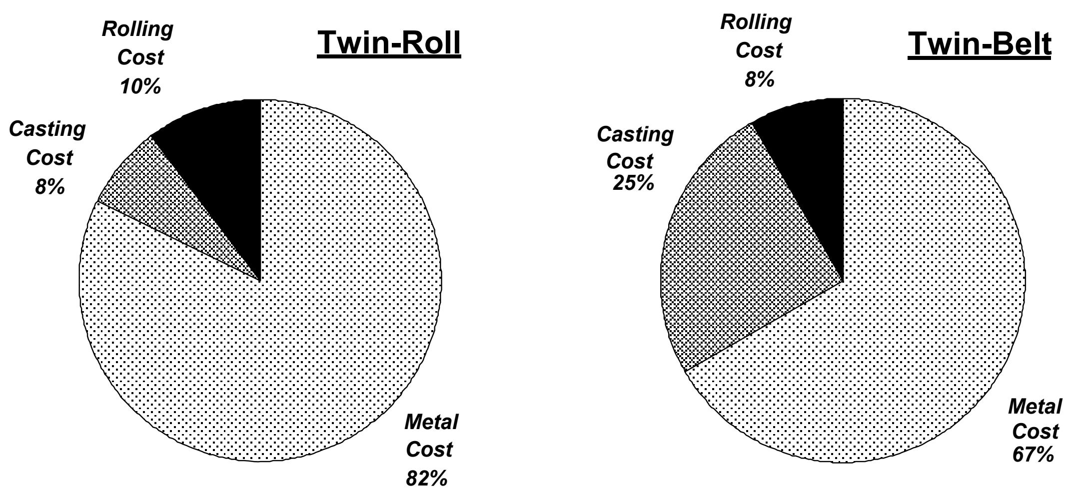

Figure 1. Percentage of total cost for each primary cost element

Table 4. Metal Prices

Metal Price/lb	Sheet Cost (twin-belt casting process)	Sheet Cost (twin-roll casting process)
$0.84	$1.73	$1.28
$1.47 (base case)	$2.43	$1.97
$1.60	$2.57	$2.11

Table 5. Annual Production Volume

Annual Sheet Production Volume (tons)	Sheet Cost (twin-belt casting process)	Sheet Cost (twin-roll casting process)
10,000 (base case)	$2.43	$1.97
20,000	$2.12	$1.94
30,000	$1.97	$1.92
60,000	$1.92	$1.92

of the higher production capacity of this process that is greatly underutilized in the base case. Only modest reductions in cost per pound for the sheet produced by the twin-roll casting process as a function of increased production volume are seen, provided by reduced variable costs per pound since capital utilization is already high.

Caster Productivity

In the base case, the assumption was made that the caster productivity would equal that of the lower end of the published range for aluminum on a density-compensated basis. However, there is no published information on continuous-casting productivity for magnesium sheet, and the possibility exists that caster productivity values could be higher or lower than that chosen for the base case. The effect of caster productivity was analyzed at two annual production volume levels for both of the continuous-casting processes.

For the twin-belt casting process, higher value of productivity equivalent to the high range of published values for aluminum on a density-compensated basis was used. On the lower side, an equal interval from the base case was studied on the assumption that magnesium continuous casting may have much lower productivity. The results are summarized in Table 6. The results in this table indicate that the overriding influence in the twin-belt casting process is not productivity but capital utilization, which is better at the higher production volume level.

For the twin-roll casting process, again a higher productivity value was used based on the published values for twin-roll casting of aluminum compensated for the difference in density for magnesium. Also a substantially lower productivity value was used to assess the effect of changes in the value of this variable. The outputs are shown in Table 7. For the twin-roll casting process-based product, sheet cost is reduced by increased productivity by less than 10% over the range of values examined with minor effects of production volume.

Rolling Process

Because the rolling process for magnesium sheet is reported to be more complicated and costly than aluminum, the sensitivity of sheet cost to variation in key rolling process variables was assessed. In this analysis, reduction per pass was varied from 20 to 50%, bracketing the 30% base-case value. Rolling recovery ranged from 50 to 90% to assess sensitivity. In this initial analysis, the low values of each variable were paired, as were the two high values. The results are shown in Table 8. Clearly there is a significant effect of rolling process parameters on final sheet cost over the range of values studied.

Direct Sheet Production

Recognizing the effect of rolling process costs and the potential sensitivity of cost to changes in the potentially realistic values for this process, another analysis was done using the extreme assumption that the continuous-casting processes could produce final thickness and width sheet without further rolling. We know that there are likely metallurgical aspects of the sheet structure that will require some finishing rolling process. Nevertheless, as a lower bound of sheet cost, a direct sheet processing route assuming 95% recovery of sheet from the metal input was determined. The results, calculated at two levels of production volume for each of the continuous-casting processes, are shown in Table 9. Elimination of the separate rolling process could have a significant positive effect on project sheet cost if technically feasible.

Summarizing the results of the cost modeling discussed above, the key conclusions are:

- Metal price is the key component for magnesium sheet price. It represents 66 to 82% of the total sheet cost in the base cases. Changes in metal price over a range of values representing differences in supply, source, and market conditions can result in as much as $0.83 per pound variability in the final sheet cost.
- For a continuous-casting process perspective, twin-belt casting was found to be very sensitive to assumed production volume in the range

Table 6. Caster Productivity--Twin-Belt

Caster productivity (lb/hr-in)	Sheet cost (10,000 tpy production volume)	Sheet cost (60,000 tpy production volume)
400	$2.43	$1.93
700 (base case)	$2.42	$1.92
1000	$2.42	$1.92

Table 7. Caster Productivity--Twin-Roll

Caster productivity (lb/hr-in)	Sheet cost (10,000 tpy production volume)	Sheet cost (60,000 tpy production volume)
20	$2.07	$2.01
45 (base case)	$1.97	$1.92
80	$1.93	$1.88

Table 8. Effect of Rolling Process

Reduction per Pass (%)	Rolling Recovery (%)	Sheet Cost (twin-belt casting process)	Sheet Cost (twin-roll casting process)
20	50	$3.07	$2.39
30 (base case)	75 (base case)	$2.43	$1.97
50	90	$2.19	$1.81

Table 9. Costs of Direct Sheet Production

Process	Sheet cost (10,000 tpy production volume)	Sheet cost (60,000 tpy production volume)
Twin-belt casting	$2.16	$1.66
Twin-roll casting	$1.70	$1.69

studied. Twin-roll casting was less sensitive. This is consistent with experience using these processes for aluminum, i.e., that twin-belt casting is best for serving large established markets with high volume requirements, while twin-roll casting is better suited to market development scenarios in which incremental buildup of volume is expected.

- Twin-roll casting is slightly more sensitive to changes in caster productivity than twin-belt casting, but final sheet cost is relatively insensitive to both. Effective use of the production capacity of the equipment has a stronger effect on sheet cost.
- Rolling process variables such as rolling reduction per pass and recovery have strong effects, with a variability of $0.58 to $0.88 in sheet cost over the range studied. Higher reductions per pass and rolling recovery, or even elimination of downstream rolling, would greatly reduce projected sheet cost.

Implications of Results on Magnesium R&D

A primary goal of the technical cost modeling exercise was to attempt to identify those factors that have the greatest influence on the projected cost of magnesium sheet as a potential driving force for technical development. This section discusses potential R&D directions.

Perhaps, as expected, the largest component of magnesium sheet cost in a scenario where alternate processing by continuous casting is used is the base metal price. While market factors will have the primary effect on metal cost, its importance dictates that the lowest cost processes are those that maximize conversion of metal units into final sheet product. One recommendation in this regard is to produce the cast sheet as close to final sheet thickness as continuous casting technology and final product microstructure, property, and surface quality requirements allow. A second approach is to develop alloys and processing schemes that enable magnesium to be rolled with high reductions and minimal edge cracking. Of course, this latter suggestion, if developed, would benefit magnesium sheet produced by conventional processes as well. There are reports of research in this area by Deakin University in Australia, where they are exploring magnesium alloys with the potential for 90% cold reduction (Deakin 2005).

To meet the objectives of reducing the production cost of magnesium sheet while achieving the targeted performance properties, much needs to be learned about composition, structure, processing, and property relationships. With specific relevance to the continuous-casting process routes that have been the primary subject of this study, an increased understanding of how alloy and process conditions produce the resulting microstructures is needed. Modeling of continuous-casting processes has been a focus of research and can be applied to magnesium alloys, coupled with critical experiments. Beyond this fundamental understanding we must establish the envelope of continuous-casting capabilities for magnesium, addressing aspects such as strip width, as-cast strip thickness, and casting rate and their effects on important issues such as segregation, cast grain structure, and surface quality. Underlying all of these studies is a better understanding of the relationship of alloy microstructure and sheet formability as well as other mechanical properties such as corrosion resistance, all of which are necessary for automotive applications.

Magnesium sheet production R&D has been addressed on a worldwide basis over the past few years. Efforts on twin-roll casting are being carried out in Australia at CSIRO (Liang and Cowley 2004), in Korea (Park et al. 2004), and in Germany at Thyssen Krupp Stahl (AMM 2001). Generally, these efforts, based on reports in the literature as well as personal communication with representatives from the various organizations, are focused at the pilot-scale, producing strip widths in the 600- to 700-mm width range and exploring a range of conventional and less conventional alloys. Process development work is focused not only on the continuous-casting process itself but also downstream rolling.

No apparent work is being done on twin-belt casting of magnesium, although one producer has indicated that technical feasibility was established by Dow some fifty years ago[(d)]. This may be an area of interest due to the concatenation of the casting and hot-rolling steps in the process, which would seem especially well suited to magnesium sheet production. The large volume capability and resultant capital cost of twin-belt casters may be an impediment to actively pursuing this route until the magnesium sheet market becomes much larger.

A final area of potential R&D emphasis would be in development of the spray-rolling process for magnesium sheet. While clearly at a much more developmental stage compared with twin-belt and twin-roll casting, the unique features of this process may fit well with the requirements and limitations of continuously cast magnesium alloys.

Presentations/Publications/Patents

- W.H. Hunt Jr., "Technical Cost Model for Magnesium Sheet Production," presented to USCAR, Materials Technical Team, Southfield, MI, June 8, 2005.
- W.H. Hunt Jr. and D.R. Herling, "Cost Assessment of Emerging Magnesium Sheet Production Methods," PNNL-15368, Sept. 2005.

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