Revised Model Reduces Cost Estimates

Pentium Manufacturing Cost Now Estimated at $40, Pentium Pro at $144

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We periodically refine the MDR Cost Model based on inputs from industry sources. This article presents the results of the latest revision. For more information about the Cost Model, refer to 081203.PDF and 071004.PDF.

As rapidly as microprocessor technology advances, the assumptions used to estimate manufacturing cost must also change. We recently revised the MDR Cost Model to more accurately project the cost of building high-end microprocessors. In general, these revisions have caused estimated costs to drop by 20–40%.

The revised numbers emphasize that Intel's recent price cuts maintain a solid profit margin for the company, even at the low end. For example, a 75-MHz Pentium today lists for $106; we estimate its manufacturing cost is $49. As the company moves most of its production to the 0.35-micron level this year, costs will drop further: at this level, Pentium costs about $40 to build, as Table 1 shows.

Revisions to Wafer Cost, Test Time

The MDR Cost Model retains the same basic equations as in its original design *(see 071004.PDF)*, but we have adjusted some of the input parameters. The most significant change is that wafer cost estimates have been adjusted downward. For example, we now estimate the wafer cost of Intel's 0.35-micron four-layer-metal BiCMOS process at $2,700, a 35% reduction.

The model includes in the wafer cost both the direct costs (labor and materials) to process the wafers and allocated depreciation for the fab (clean room and equipment). The latter cost is increasing at a much faster rate than the former; for a 0.35-micron process, depreciation accounts for about 60% of the wafer cost. The model assumes that fabs are running at or near full capacity; for vendors that cannot fill their fabs, the allocated depreciation becomes huge.

The equations used to calculate yield and die per wafer remain the same. An important factor in yield is defect rate. As a new process comes on line, its defect rate is high, but the rate drops as the process matures, a period that can last a year or more. We model this effect by reducing the defect rate over time from 1.0 defects/cm^2 for new processes to about 0.5 for mature processes. Thus, the cost estimate quoted for a processor in one quarter may be higher than the estimate provided in the next quarter. In particular, the figures presented here reflect the maturity of Intel's 0.35-micron process, which has been in production for about a year.

Once the wafers are processed, the die must be tested to separate the good parts from the bad. The previous model, basing test time solely on transistor count, calculated that the 3.3-million-transistor Pentium would require four minutes of test time, driving test costs to $22 per chip. The model has now been revised to account for the variety of techniques—such as scan testing (e.g., JTAG) and built-in selftest (BIST)—vendors use to reduce test time. Taking these factors into account, we now estimate the test time for Pentium (and similar chips) to be 30 seconds. This change reduces test cost significantly, to just $4 in the case of Pentium.

The good die are then packaged for sale. The model now includes revised cost estimates for PGA packages that,

	Intel Pentium	AMD 5K86	Cyrix 6x86	MIPS R5000	PowerPC 603e	PowerPC 604	Pentium Pro	Sun UltraSparc	Hitachi SH7604
Type of process	BiCMOS	CMOS	CMOS	CMOS	CMOS	CMOS	BiCMOS	CMOS	CMOS
Process dimension (drawn)	0.35 µm	0.35 µm	0.44 µm	0.35 µm	0.64 µm	0.44 µm	0.35 µm	0.47 µm	0.8 µm
Number of metal layers	4	3	5	3	4	4	4	4	2
Wafer size (mm)	200 mm	200 mm	200 mm	200 mm	200 mm	200 mm	200 mm	200 mm	150 mm
Estimated total wafer cost	$2,700	$2,200	$2,400	$2,600	$2,500	$2,300	$2,700	$2,200	$500
Die area (mm^2)	91 mm^2	181 mm^2	204 mm^2	84 mm^2	98 mm^2	196 mm^2	196 mm^2	315 mm^2	82 mm^2
Effective area	85%	75%	85%	48%	65%	72%	85%	68%	75%
Gross die per wafer	297	159	122	325	275	128	128	74	177
Estimated defects per cm^2	0.6	0.8	0.7	0.8	0.5	0.8	0.6	0.8	0.5
Yield percentage	65%	40%	36%	74%	74%	38%	42%	26%	75%
Untested cost per good die	$14	$40	$55	$11	$9	$47	$50	$116	$4
Package size	296 pin	296 pin	296 pin	272 pin	240 pin	304 pin	387 pin	521 pin	144 pin
Package type	PGA	PGA	PGA	PBGA	CQFP	CQFP	MCM	PGA	PQFP
Estimated package cost	$18	$21	$21	$11	$14	$21	$40	$45	$3
Total test & assembly cost	$8	$10	$10	$6	$6	$12	$21*	$28	$1
Total manufacturing cost	**$40**	**$71**	**$86**	**$28**	**$29**	**$80**	**$144***	**$189**	**$8**

Table 1. A detailed comparison of the manufacturing costs of several leading processors shows Pentium's significant cost advantage over its major x86 competitors, although a few RISC chips deliver comparable performance at a lower cost. Pentium Pro's cost is less than that of any high-end RISC processor, including UltraSparc. *Pentium Pro cost includes 256K cache chip. (Source: MDR Cost Model)

like Pentium's, use a staggered or interstitial array to reduce cost. The model also increases the volume discount that vendors such as Intel can obtain from package suppliers. We now estimate Intel pays $18 for Pentium PGA packages.

These costs assume that a company is building a part in its own fabs and performing its own testing and packaging. A key exception to this rule is Cyrix, a fabless CPU vendor. For a product like the 6x86, the model's cost estimate reflects IBM's cost in producing the part; Cyrix purchases untested wafers from IBM and probably pays a small markup in this transaction. Companies that rely on their foundries to perform testing presumably pay a higher premium.

While fab depreciation is included in these costs, no account is made for allocated process development costs or CPU design costs. For example, Pentium is purported to have cost more than $100 million to design, but this cost comes to less than $1 per unit shipped. A low-volume processor like Alpha, in contrast, could carry hundreds of dollars per unit of amortized design costs.

Intel Retains Cost Advantage

In the Pentium-class arena, the new estimates reinforce Intel's cost advantage. We now project the cost of AMD's 5K86 to be $71 and Cyrix's 6x86 at $86, about twice the cost of Pentium. The primary difference is the die size of the parts: in a 0.5-micron process, Pentium is 27% smaller than the 6x86 while using one less metal layer. At the 0.35-micron level, Pentium is 43% smaller than the 5K86, although the Intel part requires one additional metal layer. Intel also gains a cost advantage over its competitors through sheer economies of scale, particularly in the packaging area.

Intel's competitors will gain slightly over time, as their parts are early in the learning curve and so have more room to fall in cost. Cyrix is already preparing to shrink the 6x86 to a 0.35-micron process, shaving $6 off the cost. As both AMD and IBM (Cyrix's main fab) gain more experience at the 0.35-micron level, defect rates will fall and the costs of the 5K86 and 6x86 will drop to around $58 and $64, respectively. These costs will still be 50% larger than Intel's.

But when Intel deploys its forthcoming P55C Pentium, its manufacturing costs are likely to rise slightly due to the larger die of that chip. We estimate that the P55C's larger caches and other enhancements will increase the die size by 10–20%. Because of the relatively small size of the current P54C design, however, the model calculates that this increase will add just $2–$4 to the total chip cost.

Next-Generation Chips See Gains

The adjustment in costs had its biggest effect on the most advanced chips with the highest transistor counts. The cost estimates for next-generation RISC processors such as the MIPS R10000, UltraSparc-1, and the 0.5-micron 21164 all dropped to about $200 or below. At nearly $300, HP's PA-8000 remains the single-chip cost champion, due to its enormous die and generous (and still unspecified) pin count.

	Process	Die Area	Package	Est. Cost
R4700	0.60μ, 3M	73 mm²	MQUAD-208	**$23**
MicroSparc	0.80μ, 2M	225 mm²	TAB-288	**$26**
PowerPC 603	0.64μ, 4M	85 mm²	CQFP-240	**$26**
Cyrix 5x86	0.64μ, 3M	144 mm²	PGA-168	**$35**
PowerPC 601+	0.33μ, 5.5M	74 mm²	CQFP-304	**$41**
Pentium	0.50μ, 4M	148 mm²	PGA-296	**$49**
PowerPC 604	0.64μ, 4M	196 mm²	CQFP-304	**$57**
PA-7150	0.80μ, 3M	196 mm²	PGA-504	**$77**
PA-7100LC	0.80μ, 3M	196 mm²	PGA-432	**$86**
MicroSparc-2	0.50μ, 3M	233 mm²	PGA-321	**$92**
21064A	0.50μ, 4.5M	166 mm²	PGA-431	**$98**
PA-7300LC	0.50μ, 4M	259 mm²	PGA-464	**$101**
UltraSparc-2	0.29μ, 5M	149 mm²	PGA-521	**$108**
HyperSparc*	0.40μ, 3M	135 mm²	MCM-131	**$147**
PA-7200	0.55μ, 3M	210 mm²	PGA-540	**$153**
21164	0.35μ, 4.5M	209 mm²	PGA-499	**$166**
R10000	0.35μ, 4M	298 mm²	PGA-527	**$176**
Pentium Pro*	0.50μ, 4M	306 mm²	MCM-387	**$182**
21164	0.50μ, 4.5M	310 mm²	PGA-499	**$205**
PowerPC 620	0.44μ, 4M	311 mm²	CBGA-625	**$211**
PA-8000	0.50μ, 4M	345 mm²	PGA-700?	**$292**
Power2*	0.72μ, 4.5M	161 mm²	MCM-736	**$486**

Table 2. The manufacturing costs for other desktop RISC and x86 processors span a wide range. *multichip module; die area is for CPU chip only. (Source: MDR Cost Model)

These cost advantages apply to Pentium Pro as well. As Table 2 shows, the 0.5-micron version now comes in at $182, comparable to the high-end RISC chips, but the Intel processor includes 256K of cache not found on the RISC products. The 0.35-micron Pentium Pro, with 256K of cache, costs just $144. Of course, the RISC chips also benefit from a process shrink; for example, UltraSparc-2, which Sun expects to ship in 3Q96, drops to $108 in a more advanced process.

The PowerPC chips fare well against Intel's. The 603e, which delivers integer performance comparable to a 0.5-micron Pentium, costs just $29 to build, much less than Intel's cost. The 0.35-micron Pentium reduces this gap, but cost of the 603e will fall when it, too, moves to the 0.35-micron level in 2Q96. The 133-MHz 604 fares less well; at $80, it is twice the cost of Pentium, although it delivers slightly better performance. Of the other RISC families, MIPS is the only one to deliver Pentium performance at a lower cost: the R5000 comes in at just $31.

The changes in the model had a similar effect on embedded processors. Hitachi's SH7604, shipping in high volume to Sega, fell from $11 to $8, for example. *(See* **1004CW.PDF** *for more cost data on embedded chips.)*

The model shows the best route to low cost and high performance is to move to leading-edge processes as quickly as possible while keeping die size below 100 mm². With Intel leading the IC process race and in compacting its designs, it dominates the other x86 vendors in cost/performance while staying ahead of many of the RISC vendors as well. ◨

MDR frequently updates its cost model to improve its accuracy. We welcome your feedback; please contact us.