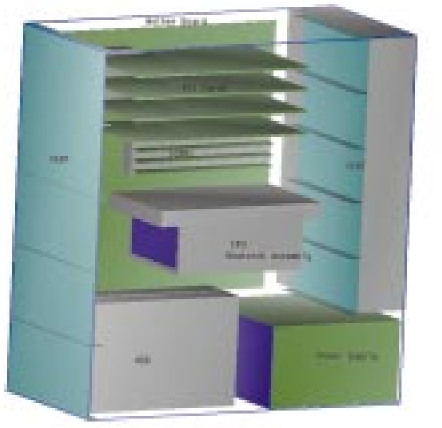
BILL TRAVIS, SENIOR TECHNICAL EDITOR

Keeping HAL cool in 2003

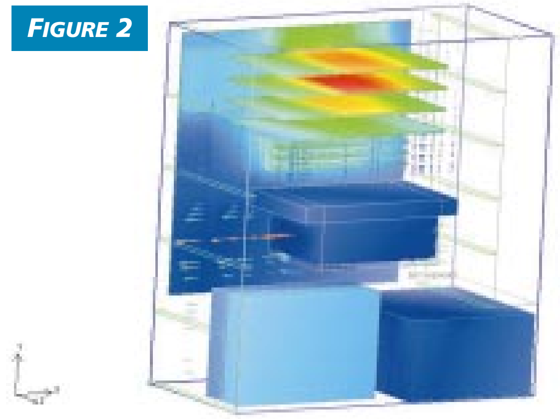
HAL in Stanley Kubrick's "2001" had deep space to keep it cool. Lacking that luxury, *EDN* worked with multidisciplined thermal-engineering experts to cool a supercharged computer from the year 2003 within tight budget constraints.

FIGURE 1



Our Year 2003 Computer resembles today's machines in construction, with a CPU, a motherboard, a power supply, disk drives (but no floppy), memory boards, and PCI-slot cards.

FIGURE 2



Before we tamed its heat problems, our computer could cook a pizza. Simulation shows a 493°C hot spot in the PCI-slot area.

Computers, just like the ICs that go into them, obey Moore's Law by doubling (or more than doubling) in performance every four years or so. It's difficult to imagine the capabilities of a year-2003 desktop machine, but it's sure that the machine will outperform the Cray supercomputers of yesteryear. This dazzling performance will surely exact its tolls in thorny high-frequency design challenges and especially in getting the heat away from power-hungry components. In this Hands-On Project, we explore the thermal-engineering aspects of a projected future desktop computer, which we call the Year 2003 Computer.

For this project, we enlisted the aid of Aavid Thermal Products and its sister divisions, Applied Thermal Technologies and Fluent. Aavid, in turn, consulted with system-packaging experts from Palo Alto Products International. The roles of the respective participants were as follows:

- Palo Alto: Design the Year 2003 Computer chassis and case, based on projections of the form factors of the various computer subsections. Goals for the chassis and enclosure designs included aesthetics, upgradability, slot and port accessibility, and ease of manufacturing.

- Applied: Based on overall system constraints, generate possible cooling-system models that use various fan, heat-sink, vent, and baffle configurations.
- Aavid: Generate projected designs for the cooling-system hardware, including heat sinks, interfaces, fans, and attachment methods.
- Fluent: Using IcePak computational-fluid-dynamics (CFD) software, provide thermal analyses, or temperature profiles, of the various cooling configurations from Applied and Aavid.

The Aavid/Fluent contributions are interactive. Fluent's CFD results, based on the system geometry, airflow, and device dissipation, are determining factors in the thermal parameters (thermal resistance in degrees Celsius per watt) required in Aavid's cooling devices.

The Year 2003 Computer

Lacking a crystal ball, no one can predict with any certainty what computer performance and power dissipation will be like five years from now. The best we can do is extrapolate from historical trends and solicit informed guesses from industry experts. **Figure 1** shows what the innards of the Year 2003 Computer might look like. The four cards at the top occupy PCI slots; the block immediately below these cards contains two-sided RAM cards. The CPU, at approximately the center of the motherboard, has a fan-heat-sink assembly attached to its bottom. The power supply is in the lower right, and the two blocks in the lower left are a digital-versatile-disk (DVD) drive (which will no doubt be rewriteable in 2003) and a hard-disk drive. The left side of the computer is one large vent.

@a glance

- Future computers will place severe demands on cooling systems, but cost constraints will rule out exotic cooling techniques.
- Without computational-fluid-dynamics simulation, it is virtually impossible to design an optimum cooling system.
- The goal of a cost-effective thermal design is to maximize the passive/active cooling-device ratio.
- An actual computer in 2003 may differ wildly from the one projected here, but the cooling principles will remain the same.

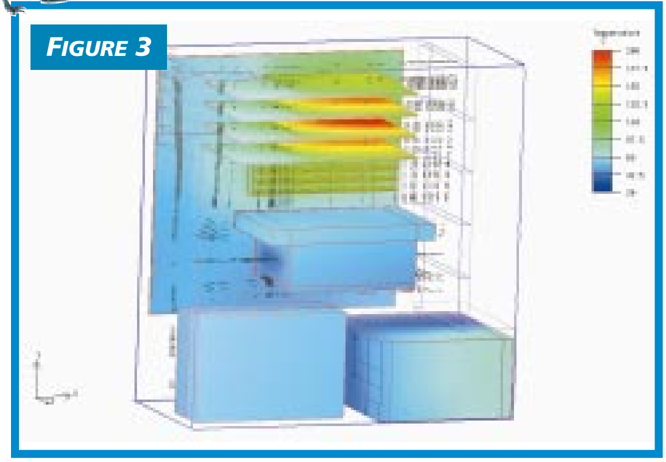
Table 1 gives educated guesses of the power-dissipation figures for each block in the Year 2003 Computer. The CPU, for example, dissipates 100W when it operates at full speed (1 GHz?). Extrapolating from the continuing trend in diminishing supply voltages, we guess that the µP might consume 100A at 1V, for example. **Table 1** indicates that the main cooling challenges lie in the CPU, the hard-disk drive, and the components on the PCI cards. The 70W in the power supply is not a major concern; it's distributed among the several rectification elements in the supply, which are relatively easy to keep cool (at 150°C maximum junction temperature, for example) using passive heat sinks.

The power-dissipation figures in **Table 1** and the resulting local temperatures assume that all systems in the computer are operating at full speed. Speed and high transistor count are the major heat-producing factors in the Year 2003 Computer. The CMOS-based CPU, PCI, and graphics chips dissipate no static power, but when they run at full speed, it takes real current (and a lot of it) to charge and discharge millions of tiny capacitors. It's a rare occurrence that everything in a computer runs simultaneously at full speed, but it's nonetheless necessary to design for that scenario.

Start the simulations

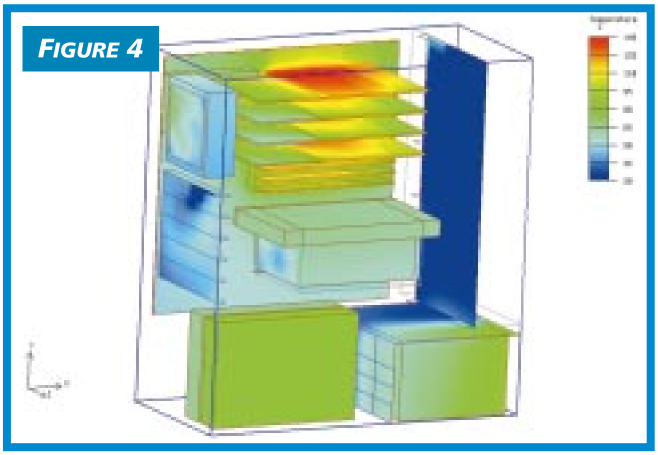
The goal in simulating the various cooling configurations was to determine the local temperatures throughout the Year 2003 Computer and then come up with classic cooling solutions (passive and fan-based heat sinks) to bring the "hot-spot" temperatures to within safe levels. We emphasize "classic" here for cost considerations. It

FIGURE 3



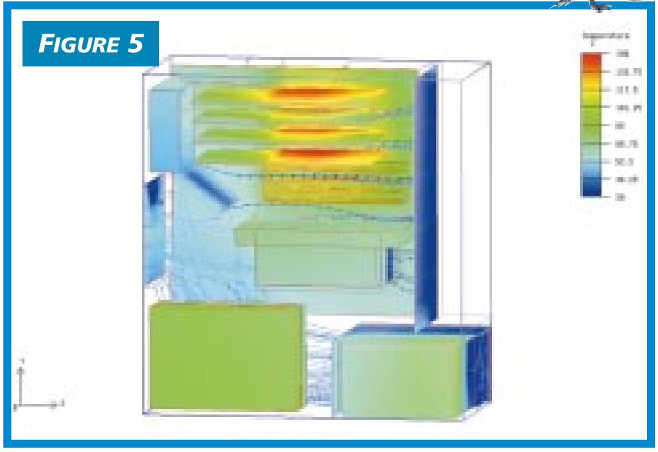
Installing a small vent facing the PCI section and closing up the rest of that side of the computer allow air to route through the PCI section and cause the temperature to drop by almost 300°C.

FIGURE 4



Adding a fan to Figure 3's design and moving the small vent just below the fan produce a manageable 140°C maximum hot spot in the PCI section.

FIGURE 5



An idea gone sour, adding a slanted baffle to the design in Figure 4, simply makes things worse by approximately 10°C.

would be relatively easy to devise an exotic cooling system using heat pipes, thermoelectric coolers, or passive or pumped liquid coolants for even the most inefficient thermal designs. However, in 2003 (as now), cost containment will be a primary consideration in computer design.

The beauty of CFD software is that using it eliminates the need to build physical models. The software solves a slew of hairy nonlinear differential equations with boundary conditions to provide an accurate prediction of local temperatures in a system. Without CFD, you'd need to construct physical models, either with actual or simulated power-dissipating components and then use sensors, temperature-indicating wax or stick-ons, or infrared instrumentation to measure the local temperatures.

The IcePak simulation in **Figure 2** shows the shocking results for the large-vent computer in **Figure 1**. This configuration uses two fans for the heat sink on the CPU and no fan for the PCI slots. The maximum temperature in the PCI section is 493°C, leading to instant incineration of the components in that section. No type of heat sinking, whether passive or active, can bring the case temperatures down to safe levels. The problem here is the lack of moving air in the PCI section. The four PCI cards are so densely packed, they turn that section of the Year 2003 Computer into a virtual oven. Heat in the stagnant spaces between the cards has no chance to escape.

How do you get air moving in the PCI section? In **Figure 3**, we use a small vent facing the PCI section and close up the rest of that side of the box. The small vent forces the air from the CPU fan to pass through the PCI section. This modification results in an almost 300°C drop in hot-spot temperature, to approximately 200°C. The PCI components now merely fry, rather than explode or burn up in a puff of smoke.

A 200°C case temperature is still too high to bring down with classic heat sinking; therefore, the PCI section requires some active heat removal. The temperature plots in **Figures 2** and **3** show that the dual-fan/heat-sink assembly keeps the CPU as cool as a cucumber, so it makes sense to remove one of the CPU's fans and use it to move air in the PCI section.

Placing a fan directly opposite the PCI slots and moving the small vent directly below the fan result in the IcePak temperature plot in **Figure 4**. The hot-spot temperature in the PCI section now drops to a respectable 140°C, a level that's amenable to management using classic finned heat sinks on the PCI-card components. The temperatures at the CPU, power supply, and disk drives are well within any conceivable design specs. Note that **Figures 2** and **3** show airflow patterns (particle traces); this feature is disabled in **Figure 4**, for a less cluttered picture of the temperature profile.

If it ain't broke, don't fix it

A great production manager in my days at Sprague Electric had a sign on his wall: "For every new product, there comes a time to shoot the engineer and go into production." The message is, if a product is producible and can meet its intended specs, don't tinker with it.

WHAT ABOUT NOTEBOOKS?

Designing a cooling system for a year-2003 notebook computer will be both easier and more difficult than designing such a system for a desktop computer. Easier, because the cost constraints are much looser. According to Chris Chapman, computer industry manager at Aavid, a notebook's cooling system traditionally costs approximately three times that of a desktop system. But that's OK; buyers are willing to pay much more for powerful notebooks than they'd pay for a desktop machine. The thermal design is more difficult for a notebook because of space constraints.

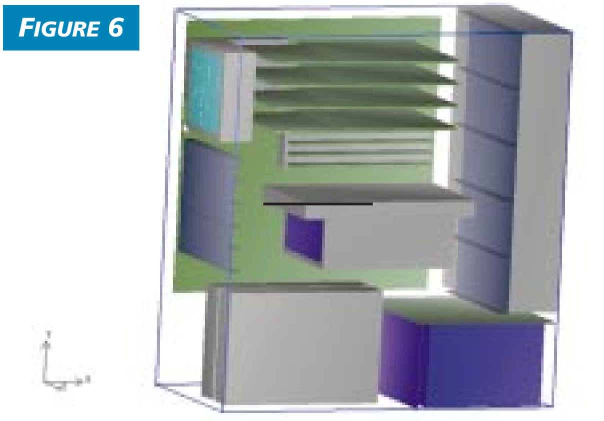
Because of severely limited space, cooling systems for a notebook must be more efficient than those for a desktop. One solution notebook makers are adopting to get the heat away from power-consuming components is the use of heat pipes to conduct the heat to a small, efficient fan. Another solution, once proposed and now all but abandoned, is to use a liquid coolant to carry the heat to the rear of the display. Orientation (gravity) problems made the liquid system impractical. However, future notebooks may use heat pipes to do much the same thing—that is, carry heat through the hinges to the display panel for dissipation.

Manufacturers of notebooks are turning to thermally conductive plastic or metal (magnesium) case material, to facilitate heat removal. Interface materials, such as High-Flow and Gap Pad from Bergquist, can carry heat directly from components to the notebook's case. Notebook makers can also alleviate thermal problems by using more efficient ICs. Silicon-on-insulator (SOI) ICs consume much less power than all-silicon devices for equivalent performance. Again, the SOI devices are more costly, but in a notebook, cost is not an overriding consideration.

Ignoring that advice, we decided to see if we could improve the thermal design used for **Figure 4**'s results. The idea was to insert an inclined, solid-plate baffle below the fan in the PCI section to see if the thermal pattern in that section would change favorably. Unfortunately, the addition of the baffle (**Figure 5**) made things worse, increasing PCI-component temperatures by approximately 10°C.

The design in **Figure 6** is thus the optimum thermal design for the Year 2003 Computer. Given the temperature profile in **Figure 4**, our remaining task was to design cooling components that bring the simulation-result temperatures within design limits. **Table 2** expands upon **Table 1** to show the cooling-component requirements and gives estimates of the costs of the collection of cooling devices.

FIGURE 6



The final configuration of the Year 2003 Computer uses approximately $15.50 worth of cooling components to remove 335W of heat.

FIGURE 7

Tom Shoda's conception of the Year 2003 Computer is sleek and streamlined. We'll see how close it comes to reality in five years.

The case-temperature figures in **Table 2** apply to the active devices in the various computer sections. The ICs in the mass-memory sections and on the PCI cards are the most critical, requiring 65 and 70°C maximum case temperatures, respectively, for optimum performance. The devices in the power supply are the least critical; most power semiconductors are rated for junction temperatures of 150°C and higher. The heat-sink requirements in thermal resistance are calculated to bring the hot-spot temperatures shown in **Figure 4** down to permissible case temperatures.

According to Chris Chapman, computer-industry manager at Aavid, the CPU in the Year 2003 Computer will most likely use an extruded, finned heat sink with an integral fan. (An alternative heat sink is one folded from sheet metal with a fan attached.) To attain the low 0.45°C/W thermal resistance, the sink needs intimate thermal contact with the CPU block. Chapman proposes the use of a thermal-interface product, such as Bergquist's Hi-Flow, a filled polymer that replaces thermal grease. At a certain temperature (for example, 65°C), Hi-Flow changes from a solid to a viscous form and flows; thus, it acts like ther-

FOR MORE INFORMATION...

For more information on the products and services we used in this Hands-On Project, circle the appropriate numbers on the Information Retrieval Service card or use *EDN*'s Express Request service. When you contact any of the following vendors directly, please let them know you read about their products or services in *EDN*.

Aavid Thermal Products Inc
Manchester, NH
1-603-629-2235
fax 1-603-669-3967
www.aavid.com
Circle No. 301

Applied Thermal
Technologies Inc
San Jose, CA
1-408-522-8730
fax 1-408-522-8729
www.cool-it.com
Circle No. 302

Bergquist Co
Minneapolis, MN
1-612-835-2322
fax 1-612-835-0430
www.bergquistcompany.com
Circle No. 303

Fluent Inc
Lebanon, NH
1-603-643-2600
fax 1-603-643-3967
www.fluent.com
Circle No. 304

Palo Alto Products
International
Palo Alto, CA
1-650-617-9618
www.paloaltoproducts.com
Circle No. 305

VOTE . . .
Please also use the Information Retrieval Service card to rate this article (circle one):
High Interest 582
Medium Interest 583
Low Interest 584

Super Circle Number

▶ For more information on the products available from all of the vendors listed in this box, circle one number on the reader service card.

Circle No. 306

mal grease. Its thixotropic characteristics keep the Hi-Flow from flowing out of the interface area.

The hard-disk drive uses a thin, finned heat-sink plate that attaches to the drive housing. In the DVD drive, Aavid's A-Pli interface material provides a thermal path from the drive's internal chips to the outer casing. A "sandwich" arrangement helps cool the RAM chips. Board-length heat-sink plates make contact with the RAM chips on both sides of the memory boards through Gap Pad, an interface material called from Bergquist. The heat sinks act as both heat removers and heat spreaders, equalizing the temperatures of the RAM chips.

TABLE 1—POWER DISSIPATION IN THE YEAR 2003 COMPUTER

Computer section	Power dissipation (W)
CPU	100
Hard-disk drive	30
DVD drive	10
Memory	10
Graphics	10
PCI controller	5
PCI cards	4x25=100
Power supply	70 (350W at 80% efficiency)
Total	335

Keeping costs down was a primary consideration of the Year 2003 Computer project. One way to cut cost is to minimize the number of active, fan-based coolers and use inexpensive extruded or stamped active heat sinks wherever possible. The design in **Figure 6** uses only two added fans: the integral fan in the CPU's heat sink and the vent fan for the PCI slots. (The power supply contains its own fan.) The PCI controller and the graphics controller use extruded, finned heat sinks; the PCI-card devices and the power-supply semiconductors use a combination of stamped and extruded heat sinks.

The estimated cost for the cooling components in the Year 2003 Computer is $15.50. For 335W power consumption, the cooling cost is $0.046 per watt of system dissipation. Today, a typical computer might dissipate 120W and contain $8 worth of cooling devices, for a cooling cost of $0.067 per watt of system dissipation. You can contain the future computer's cooling-system cost only by using an optimum thermal design, and you can find that optimum design only by using CFD tools, such as Fluent's IcePak. A poor thermal design for the future computer could result in a cooling-system cost as high as $35.

TABLE 2—COOLING SYSTEM FOR THE YEAR 2003 COMPUTER

Computer section	Power (W)	Case temperature (°C)	Heat-sink requirement (°C/W)	Estimated cost
CPU	100	85	0.45	$5
Hard-disk drive	30	65	0.83	$1.25
DVD drive	10	65	2.5	$0.75
Memory	10	85	4.5	$1
Graphics	10	85	4.5	$0.75
PCI controller	5	85	9.0	$0.75
PCI cards	100	70	1.0	$3
Power supply	70	110	1.0	$3
Total	335			$15.50

This Hands-On Project revealed some important aspects of thermal engineering. Perhaps the most valuable thing we learned is that it's possible to apply today's cooling techniques and devices to tomorrow's systems in a cost-efficient way. Emerging technologies may make our guesses about the projected Year 2003 Computer wildly off the mark, but the simulation and thermal-engineering principles discussed here will nevertheless remain valid, no matter what form the computer assumes. **Figure 7** is Palo Alto Senior Industrial Designer Tom Shoda's computer-generated rendering of what a Year 2003 Computer might look like.

Acknowledgments

EDN *wishes to thank the individuals involved in the Year 2003 Computer task force. Chris Chapman, computer-industry manager at Aavid, coordinated the efforts of the four contributing companies. Tom Shoda, senior industrial designer at Palo Alto, provided the chassis layout and case design of the future computer. Engineer Prabhu Sathyamurthy at Fluent performed the CFD analyses. Vivek Mansingh, executive vice president and general manager at Applied Thermal Technologies, provided the cooling-configuration models for Aavid and Fluent to work with. And last, but by no means least, Aavid's marketing/communications manager Judie Hart applied constant, gentle prodding to all of us to keep on schedule and managed the enormous amount of artwork (approximately 1.6 Gbytes, in high-resolution .tif files) the project generated.*

You can reach Senior Technical Editor Bill Travis at 1-617-558-4471, fax 1-617-558-4470, e-mail b.travis@cahners.com.

VOTE

Please use the Information Retrieval Service card to rate this article (circle one):

High Interest	Medium Interest	Low Interest
582	583	584