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Heat Pipes

Your computer may be using this technology to cool the CPU. Learn how you can use heat pipes in your Amateur Radio station.

Many hams will think of heat pipes as new devices, but in reality they have been around for more than 30 years. It is just that it is only relatively recently that these devices have been perfected and placed into the commercial consumer marketplace. More than 20 years ago I studied the application of heat pipes to solve a difficult thermal problem in the AMSAT Phase 4 satellite (geostationary ham radio communications platform).[1] At that time I found a (then) 10+ year old reference and description of heat pipes.[2]

Study Figure 1 and the following description and you will get the idea: "The heat pipe is a thermal linkage of very high thermal conductivity. It is a closed, evacuated chamber lined with a wick. Heat is transported by evaporation of a volatile fluid, which is condensed at the cold end of the pipe and returned by capillary action to the hot end. The vapor passes through the cavity. Heat pipes consist of three zones or sections: the evaporator, the condenser and an adiabatic section connecting the two. In some designs the adiabatic section may be very short. This device offers a number of important properties useful in electronic equipment cooling systems. It has many times the heat transfer capacity of the best heat-conducting materials, while maintaining an essentially uniform temperature and transporting heat over distances of several feet. It requires no power and operates satisfactorily in a zero gravity environment."

[For readers unfamiliar with the physics of heat transfer, it may be helpful to turn to a definition of an adiabatic process, such as can be found on Wikipedia (**http://en.wikipedia.**

[1]Notes appear on page 9.

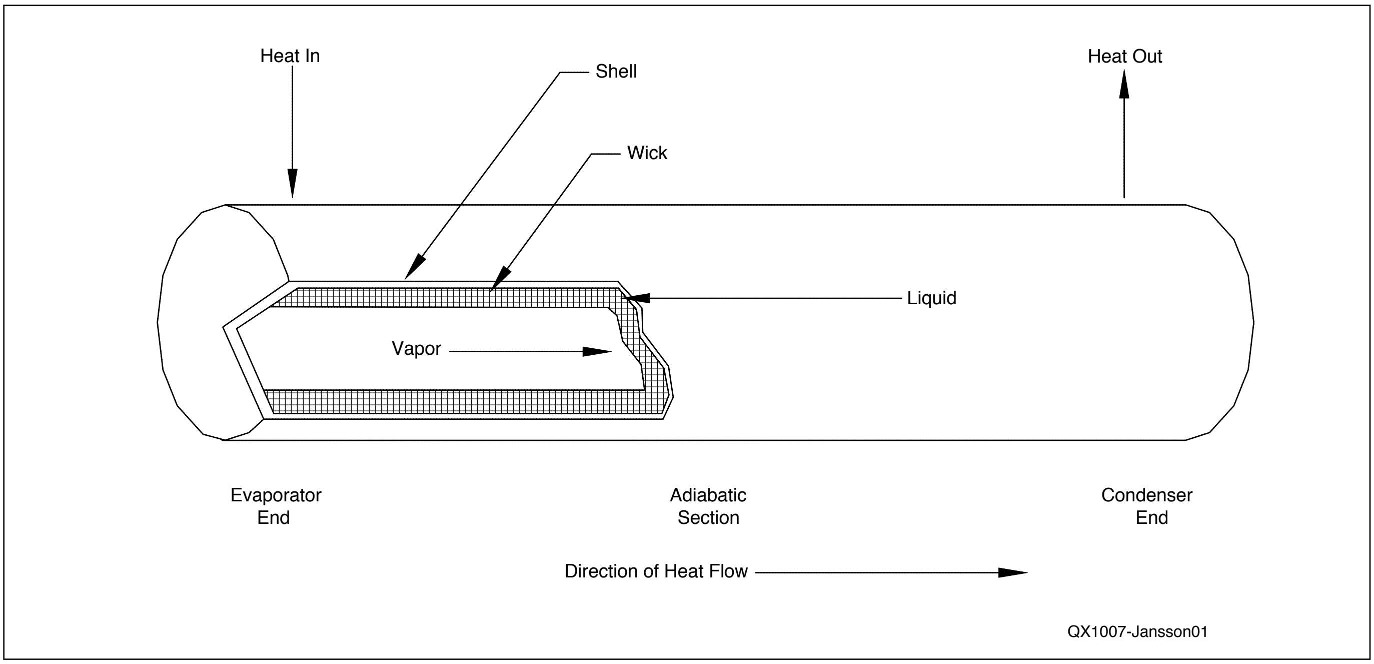

Figure 1 — Heat pipe basics. KD1K drawing

org/wiki/Adiabatic_process). The short definition, taken from the Wikipedia source, is that an adiabatic process is a thermodynamic process in which no heat is transferred to or from the working fluid. For example, adiabatic heating occurs when the pressure of a gas is increased from work done on it by its surroundings, such as by a piston. Diesel engines rely on adiabatic heating during their compression stroke to elevate the temperature sufficiently to ignite the fuel. Adiabatic cooling occurs when the pressure of a substance is decreased as it does work on its surroundings. — Ed.]

Putting this description into other terms,

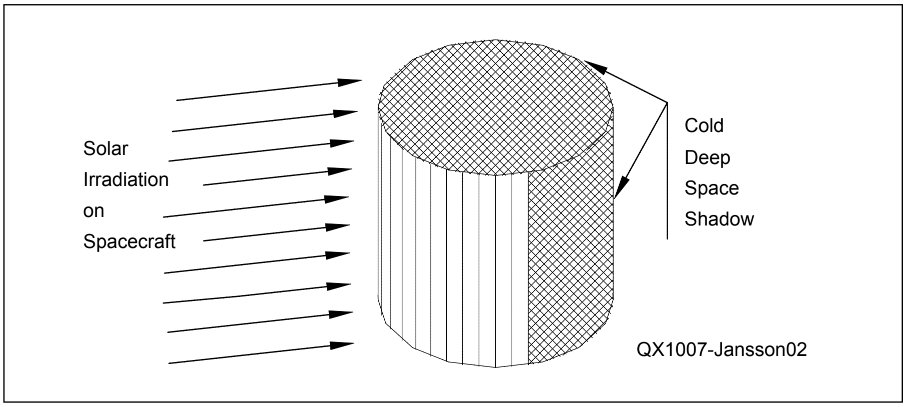

Figure 2 — Solar heating problem for stabilized, pointing satellites. KD1K drawing

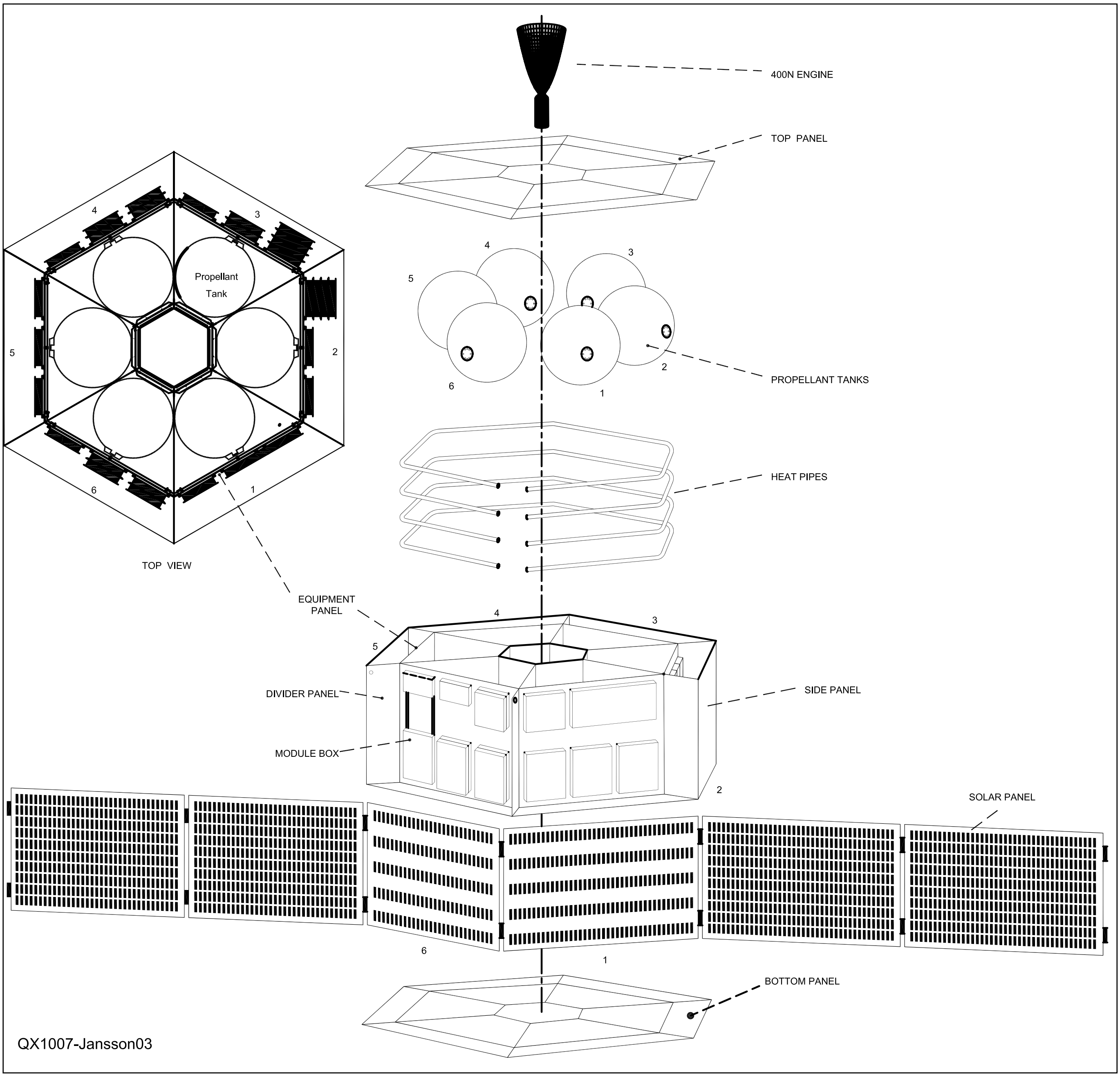

Figure 3 — Exploded view of AO-40 spacecraft, showing major components and heat pipes. Wilfred Gladisch, AMSAT-DL, drawing

a heat pipe is a linear thermal conductor that is hundreds to thousands of times better than the purest of copper or silver bars — they just don't get any better than that.

The applications and materials of heat pipes have been perfected over the years into some truly meaningful devices. Spacecraft heat pipes are considerably more demanding than those used in the commercial applications, such as the cooling of modern-day computer CPUs. I shall try to illustrate these differences and also to show how you can use heat pipes.

Space Application

One space application that has been experienced is that of the AMSAT AO-40 (formerly the Phase 3 D (P3D) Program before being launched and placed into service). Recalling the AO-40 effort will illustrate the evolution of its thermal design. Because of the spacecraft size, the thermal activities happening on one side of the spacecraft would not significantly affect another side. In a stabilized, "pointing mode" orientation, one side would continuously face the Sun, while the opposite side would never see any sunshine. See Figure 2. As a result, the sun side would become quite warm while the back side would get dreadfully cold, all of this even though the structure is made of aluminum, which is thought of as a pretty good heat conductor. In these dimensions, sheet aluminum structures of the size of AO-40 are incapable of moving enough thermal energy to make a difference in this matter.

In addition to solar heating, the RF transmitters installed in AO-40 had outputs up to 300 W PEP, with average power dissipation levels in the 25 to 75 W categories. This meant that there were power transistors (MOSFET devices, actually) with quite small mounting surfaces trying to get rid of tens-of-watts of power. Numerically, heat fluxes of 30 W/cm^2 could be expected at the mounting face of any single transistor. To give you a feeling for this type of heat flux, the sunshine that you get at the beach on a clear summer day is in the order of 60 mW/cm^2 or 1/500th of the flux at the mounting surface of each of these transistors! To further heighten this problem of cooling of high-powered solid-state electronics, the semiconductor junction inside these devices should not be allowed to become any warmer than about 125°C for reliability reasons. These devices cannot be allowed to glow red like the handy radiant heater in your house!

The solution to all of these basic thermal problems on AO-40 was to employ the use of heat pipes inside the spacecraft. This arrangement is shown in Figure 3, which illustrates the basic six-sided prismatic structure of this spacecraft. The six Equipment Panels were mounted about 220 mm (≈8.7 inches) below the exterior side panels. The key to this design is that the equipment panels were in contact, actually bonded, with the four heat pipes and that the heat pipes were not connected directly to any external panel. The basic tenet here is that the "waste" heat removed from one part of the spacecraft was used to keep the cooler parts suitably warm, a thermal redistribution system, if you will. This thermal design concept provided for heat rejection from the spacecraft by radiant exchange between the equipment panels and the side panels, which can get very cold, as intended. As you can also see in Figure 3, all of the basic electronic modules were mounted to those same equipment panels. I do not know of other satellite designs that have used this principle.

The heat pipes used in AO-40 were a very sophisticated aluminum extrusion. These were available in a maximum length of 16 feet, just long enough to be formed into a nearly complete hexagon on the inside of the equipment panels. Working with this particular heat pipe extrusion was a continuation of efforts started with the earlier Phase 4 program. That experience was usefully assimilated into the AO-40 spacecraft. An enlarged view of this extrusion is shown in Figure 4. As you can see, the liquid "wick" is really a group of 27 closely spaced channels in the wall of the extrusion. The geometry of these channels allowed a very substantial flow of liquid returning from the "condenser section" to the "evaporator section," thus providing for an equally substantial thermal transfer rating for the heat pipe. In AO-40 use, there was no clear geometric definition for these evaporator and condenser sections, as the pipes were exchanging thermal energy with the spacecraft in many locations, but this was what was intended for this design.

While the bonding of the heat pipes to the equipment panels was sufficient for the heat exchange with the panels, such methods were insufficient for the high-powered transmitter modules. Coupling high power transistors to this heat pipe system therefore required some additional measures to be taken. Figure 5 shows a cross-sectional view of this arrangement. At the high heat fluxes presented by these transmitters, coupling to just one side of the heat pipe was not adequate. Therefore a specially machined aluminum "Heat Pipe Clamp" was made of high purity aluminum (for maximum thermal properties) and carefully bonded to each side of the heat pipe using a special fixture. Such a design step was intended to bring at least two other sides of a heat pipe into thermal contact with the module heat sink. These heat pipe clamps were, in turn, bonded to the equipment panels at the same time as the heat pipes. On the other side of this thermal path, the transmitter modules were equipped with two high-purity aluminum heat sink plates for the mounting of the power transistors. These modules were also closely mounted to the equipment panels as well as being bolted through to their respective heat pipe clamp. The final step, shown in Figure 5, was to mount the power transistor to the heat sink, using space-rated silicone grease. All of these bonding and bolting steps are necessary to insure a very high quality thermal path from the transistor to the heat pipe fluid (anhydrous ammonia, NH_3). Figures 6 and 7 are photo illustrations of these heat pipe clamps as a separate assembly and as installed in the spacecraft.

The thermal performance of this complete high-power coupling of transmitter transis-

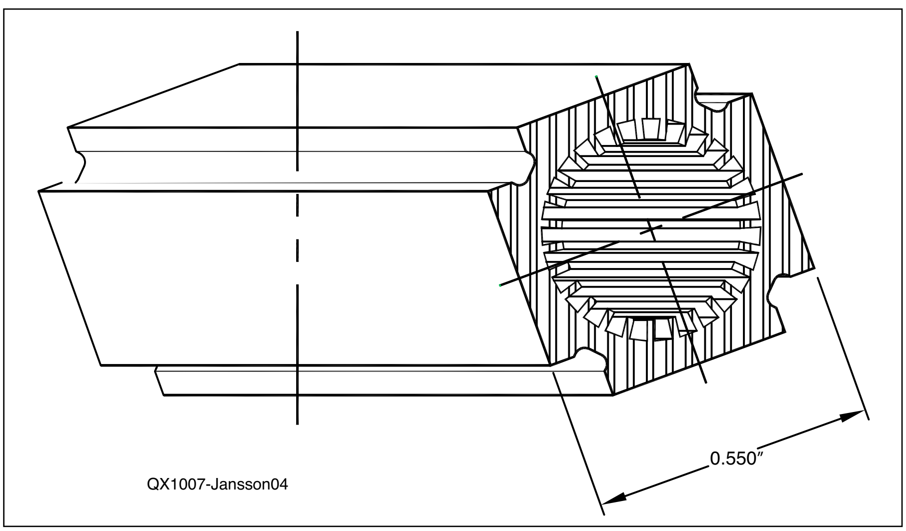

Figure 4 — AO-40 heat pipe extrusion cross section. KD1K drawing

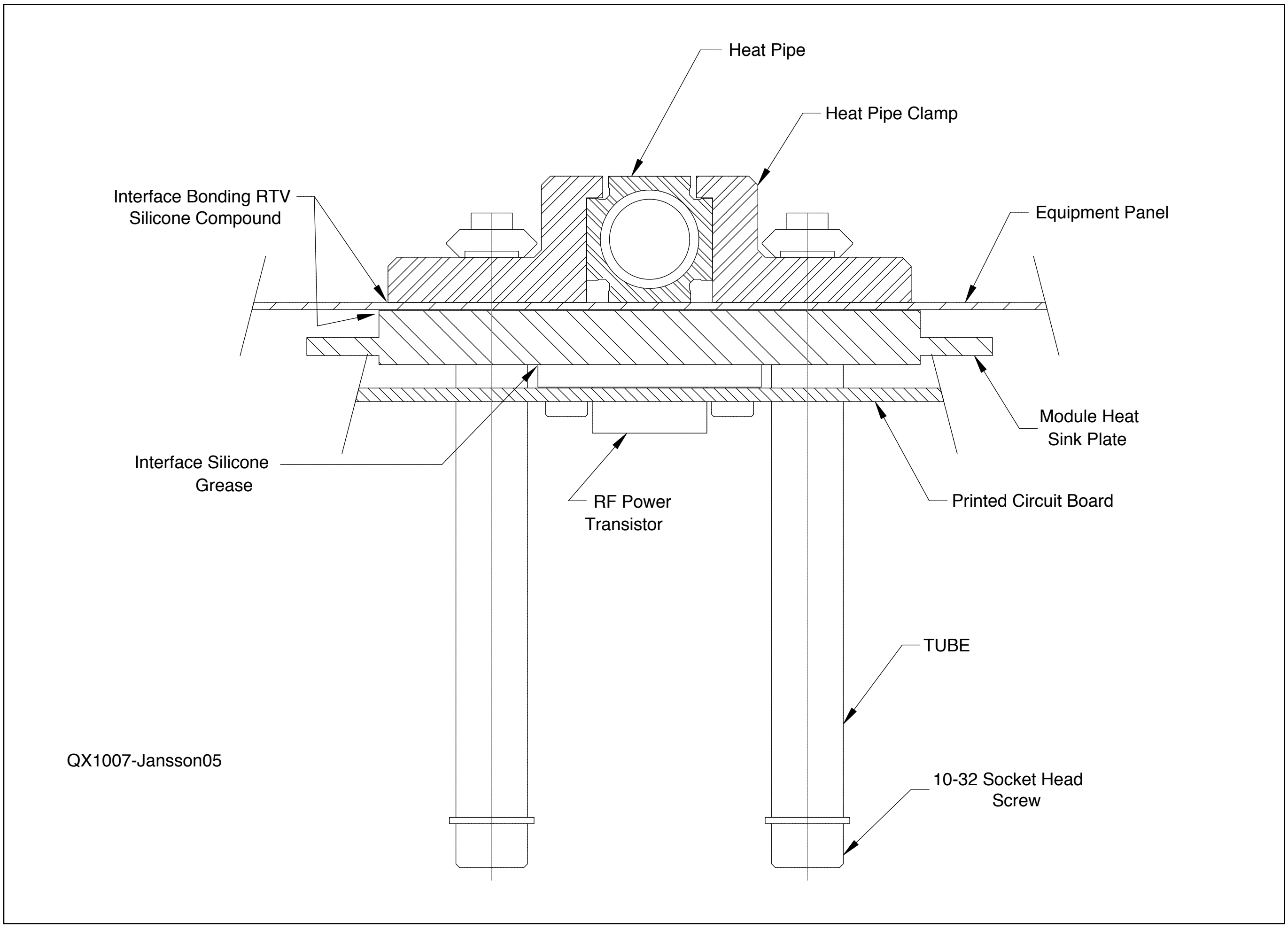

Figure 5 — AO-40 module mounting to heat pipe cross section view. KD1K drawing

tors to the heat pipe system was the subject of a fairly extensive thermal analysis as well as a specially constructed physical thermal model, including a short section of active heat pipe. Building such a thermal model was one of the extra-special fun things that I did for the AO-40 program (thermal designers are strange people, after all). The need for such elaborate evaluation is that in the vacuum of space, the satellite does not have thermally conductive air between parts, and nearly none of the parts will be in perfect contact. These "interstitial" spaces needed to be filled with a compliant material to permit the thermally conductive joining of the parts. The analyses and testing checked out the use of these various materials and I made tradeoff evaluations as a result. The "bottom line" of this effort was a transistor thermal mounting with an effective thermal resistance (between the transistor case and the heat pipe fluid) of θ_{sf} = 0.27°C/W; that is quite low, even lower than that of the transistor junction to its case. The results of this effort were

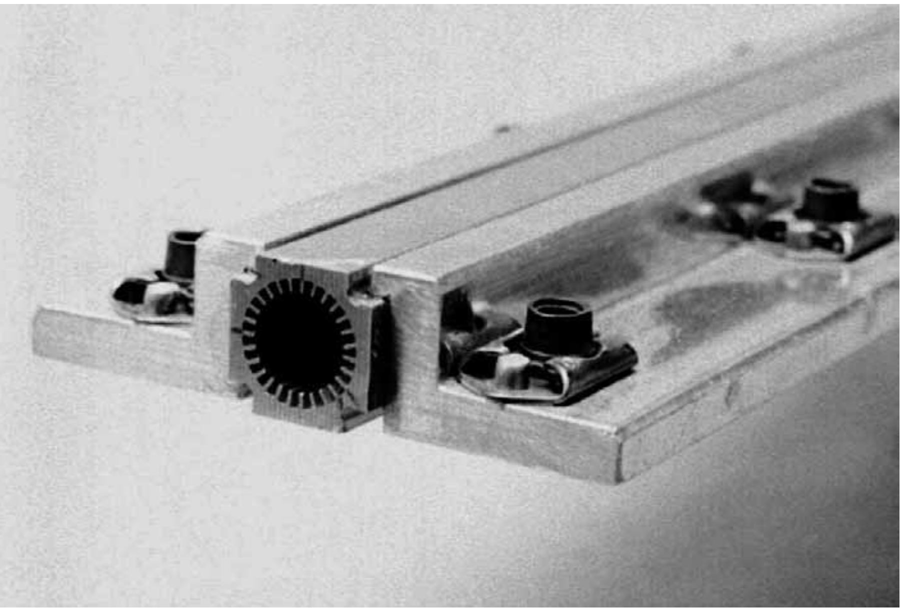

Figure 6 — AO-40 heat pipe and clamp. KD1K photo

very gratifying, as the initial concerns that it wouldn't work well had been great.

I have emphasized the use of heat pipes in space, so far — and for good reason. Heat pipes are sensitive — very sensitive — to environmental accelerations, a fancy description of the Earth's gravity. On Earth, if the evaporator section of an ammonia heat pipe is higher than the condenser section by much more than 0.1 inch in a foot of length, then the capillary forces of the liquid wick may not be strong enough to draw the liquid "up hill" and overcome these gravitational effects. If, however, the evaporator section is lower than the condenser section, then gravity will help the flow of liquid back to the evaporator section — which is how heat pipes work for computer users here on Earth. In the "gravity freedom" of space, this is not very much of a problem, as spaceflight is thought of as being in zero gravity. This is not an absolute condition, however, as spacecraft motions can cause local accelerations that can pose problems. Let me describe just such a case.

AO-40 was designed as a cylindrical spaceframe, albeit a hexagonal cylinder. It was also designed to initially spin about its principal axis until the mission was ready to stop the spin, deploy the solar panels and operate as a three-axis stabilized satellite. For reasons not germane to this discussion, the stable mode of operation was never achieved for AO-40. Spin-stabilized operation is useful for times when the orbit-adjusting propellant motor was operated, because such a spin will average out any small errors in propellant motor alignment. As a result, for motor operation, AO-40 was spun up to more than 10 rpm. Since the heat pipes were placed on the walls of a cylindrical satellite, they were nominally equidistant from the spin axis and thus saw a uniformly distributed centrifugal acceleration…except. That exception was that the heat pipes were part of a hexagonal cylindrical form, not a circular cylinder. That meant that the corners of the hexagon were farther from the spin axis than the "flats" of the hexagon. As a result these corners had a higher centrifugal acceleration (caused by the spin motion) than for the flat sides. At the low spin rate of AO-40 in normal operation, these acceleration differences were not so large as to overcome the capillary forces inside of the heat pipes, and all operated just fine.

During one of the motor-burn phases of the early AO-40 operation, the heat pipes stopped operating. There was some considerable concern by those controlling AO-40, and I was consulted on the matter. As the heat pipe operation had been very well characterized, the problem was confirmed and a projection was made of just what spin rate would again achieve operation and that computation was confirmed by the controllers as the spin rate was slowed, much to their relief — so much for zero gravity in space. There are always caveats to be addressed.

Terrestrial Applications

All successful heat pipe operations depend upon some fairly tight technical details, regardless of where a heat pipe is used. In addition to the challenging design of the fluid wick on the walls of the heat pipe, the purity of the working fluid is paramount. The fluid in the AO-40 heat pipes was anhydrous ammonia, NH_3, owing to the need for the heat pipe to operate at temperatures below 0°C and up to 40°C. The steps used to make sure that the inside of the heat pipe was truly clean was enough to make one wonder just what does "clean" really mean. Any impurity can seriously reduce the operating capability of a heat pipe, because it will result in a noncondensable gas that impairs the working fluid from getting to where it is needed.

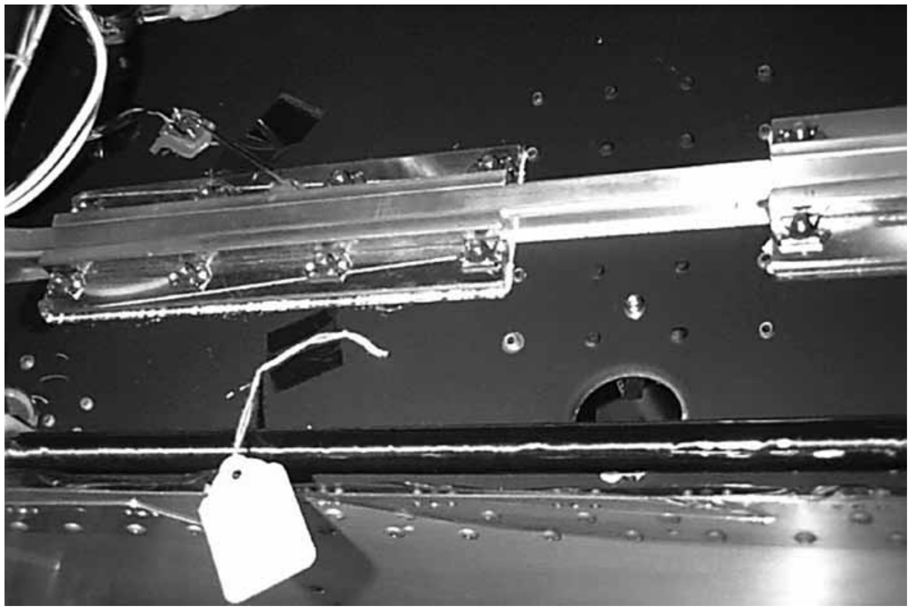

Figure 7 — Heat pipe assembly with clamp mounted inside of AO-40. KD1K photo

Figure 8 — SilverStone CPU cooling heat pipe. SilverStone Tek photo

Using a powerful and hazardous reagent like ammonia for a consumer-market device would be out of the question — but there is no need for such a heat pipe to operate at low temperatures. So the ground rules are changed. Computer heat pipes need only to operate from room temperature, ≈20°C up to perhaps 70°C. This opens the opportunity to use one of the very best heat transfer fluids that is available for us — water, just plain (but very pure) water, H_2O. The pressure inside of water heat pipes is less than 1 atmosphere (14.7 psia). For example, at 20°C the pressure would be 2.34 kPa (0.34 psia) and at 50°C a pressure of 12.3 kPa (1.8 psia) would be observed. Operating at lowered pressures, such as noted, is not a great concern because a heat pipe must be truly sealed, and water does not care until the temperatures would get nearly to freezing, 0°C.

Heat pipe wick operation will be quite good with water because the surface tension of water is relatively high, meaning that a water heat pipe wicking operation will be somewhat better in the anti-gravity situation than many other fluids can support, including ammonia. Nevertheless, the water heat pipes that I have found all are positioned in the gravity-assist position — the condenser section is located above the evaporator section.

Consumer application heat pipes come in two basic varieties, based on the materials used for the heat pipe and the CPU heat sink. You will find these heat pipes in aluminum and copper and these differences will drive other factors such as in the details of the internal fluid wick design and fabrication.

Figures 8 and 9 illustrate heat pipes that are manufactured for computer CPU cooling. This is a relatively recent application for heat pipes, driven by the ever-increasing complexity and power density of today's CPU devices. Traditionally, as electronic circuits have been miniaturized, made more complex, and made to operate with faster clock speeds, their power dissipation has also dramatically increased. The days of truly low-power CMOS devices are long gone. Consequently the computer designers have had to become much more inventive in their schemes to cool these devices – the opening for useful heat pipe applications.

Using copper in the design of a CPU heat pipe is promoted as an advantage over using aluminum, because copper has a thermal conductivity that is more than twice as high as aluminum. A disadvantage of copper heat pipes is the weight of copper assemblies, which all bear more heavily on the printed circuit board. This issue becomes a concern of PCB designers, as it is a hazard for the electrical trace integrity of the PCB itself.

Another concern in these CPU applications is that of the thermal coupling between

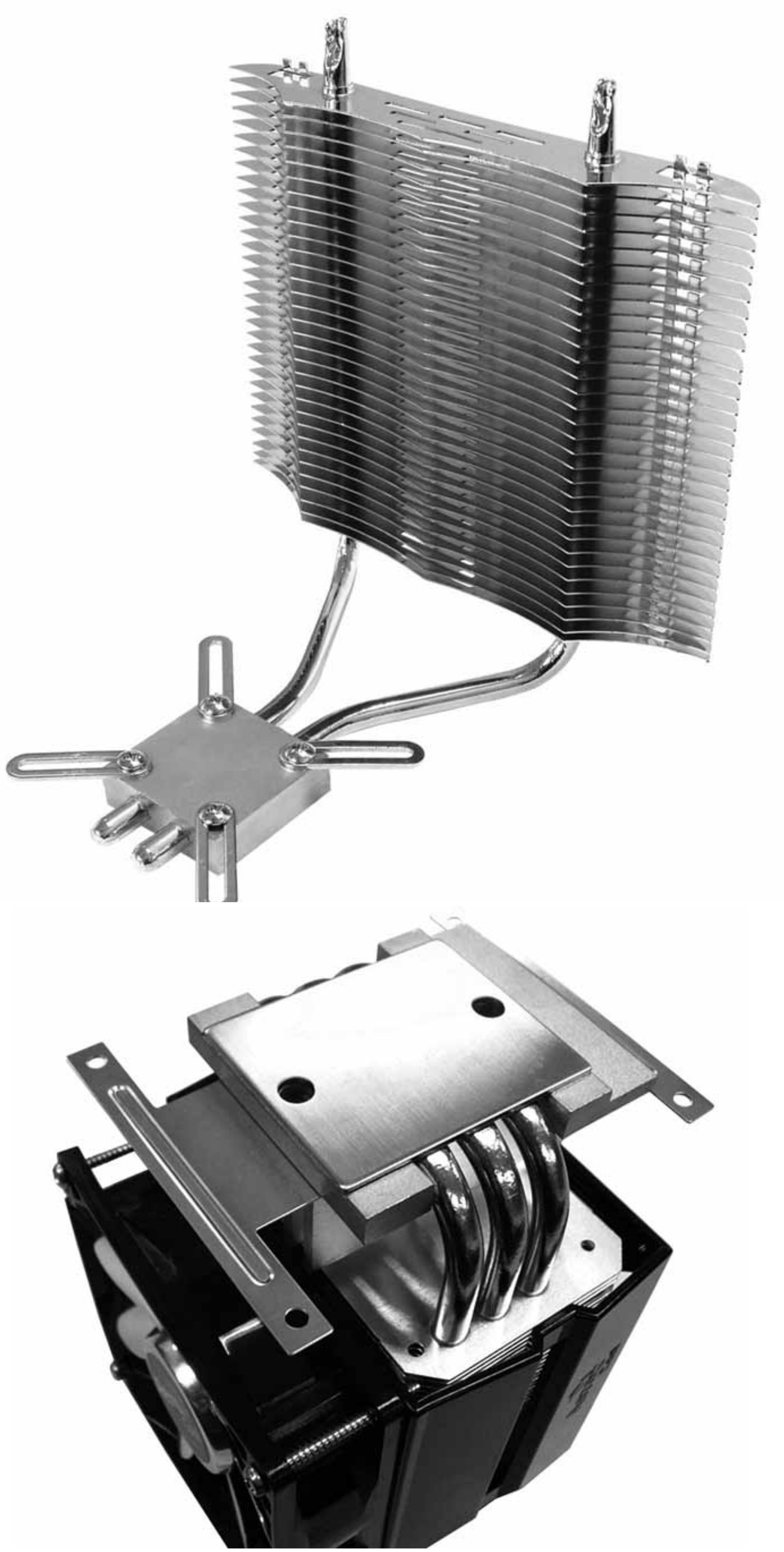

Figure 9 — AeroCool CPU cooling heat pipe devices. Note that the unit at the bottom is shown upside down to show the CPU mounting surface and the heat pipes. This unit includes a fan for extra cooling. AeroCool photos.

Figure 10 — W1TKZ 1976 Field Day 6m station; L-R unknown youth; Ed Jansson, WD4DTC (then WA1UTJ); (the somewhat younger) KD1K (then WA1QLI); with the liquid cooled 6m amplifier and the author's Yaesu FT620B transceiver. Chris Wiles, WA1RGA, photo

the CPU device and the heat pipe. CPU designers are faced with a nearly impossible nightmare task of moving the device heat out to the surface of the package to a point where a cooling device can be attached. The heat pipe designer also has the challenging problem of getting this CPU heat to the heat pipe fluid, which is the area that involves a thick copper plate (and its attendant weight) or an aluminum plate (with its lowered thermal properties). These coupling plates can be seen in Figures 8 and 9. There was a review of several of these CPU coolers in a special issue of *Computer Power User* magazine in 2005. This review gives considerable insight into the thermal issues involved with these coolers.[3] (You can also do a Google search on "heat pipe" to find this article and much more information.)

An Amateur Radio Application?

I am going to get inventive now and hypothesize how these CPU heat pipes can be used in an Amateur RF application. Suppose you have a transmitter that employs ceramic-cased high-power transistors in the output stage. Normally these devices are screw-mounted through openings in a PCB to a heat sink. This device mounting could be done instead to the underside — the CPU side — of a water heat pipe cooler, along with its PCB. The transistors would be hanging upside down, but they do not really care at all about that position. Such transistor mounting would have to be very carefully done so that any screw hardware does not penetrate the several heat pipes. Alternatively, an intermediary aluminum or copper plate could be used between the transistors and the cooler.

This conjecture reminded me that about 35 years ago I constructed a somewhat similar transmitter cooler for the home-brew compact 100 W amplifier of my 6 meter station at that time. While this cooler did not use any wicking agent inside the cooler, it had all of the other elements: a copper evaporator section in a portable cabinet, with an air-finned condenser section above the cabinet. This was operated at atmospheric pressure and employed one of the suitable (now banned) Freon liquid cleaning agents available at the time. This transistor cooler worked very well, bringing quite ample cooling into the tight space typically seen in a high power solid-state amplifier. Figure 10 shows this amplifier in action during the Field Day 1976 operations by the Wellesley Amateur Radio Society, W1TKZ. (I also very well remember that right after the opening bell, my first contact was YV5ZZ. That opened up the eyes of the HF operators.) As this was a liquid cooler operated at atmospheric pressure, it depended upon having liquid flooding the evaporator section and the necessity of a sight glass to insure that sufficient liquid was available. In a heat pipe, the sidewall wick makes that assurance.

So you can see that I have had off and on experiences with liquid cooling of power electronics, some of it considerably before becoming involved in the AO-40 experience starting in 1990. I do not currently employ any liquid coolers in my current computer and station installation, as air-cooled heat exchangers have sufficed for these applications, but I have not abandoned the concept.

Let your imagination be your guide.

Notes

[1]Dick Jansson, WD4FAB, "Spaceframe Design Considerations for the Phase IV Satellite," *AMSAT-NA Technical Journal*, Vol 1, No. 2, Winter 1987-88.

[2]*Military Handbook Reliability/Design Thermal Applications*, MIL-HDBK-251, 19 January 1978, Chap.12, p 405.

[3]This *Computer Power User* review article about some CPU heat pipe coolers is available on the Internet at: **www.computerpoweruser.com/Editorial/article.asp?article=articles/archive/u0904/52r04/52r04.asp&guid=**