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CLOSING COMMENTS: RECENT DEVELOPMENTS IN 5 K CRYOCOOLERS - AN OUTSIDER'S VIEW

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In this closing summary, I'm going to present an outsider's view of what we've heard for the past two days[1]. The reason it's an outsider's view is that given Elie Track's original list of participants, I'm neither a maker nor a user of cryocoolers and I'm not in the government, so I'm clearly on the outside. The points that I have picked to discuss today came to mind during this workshop as being important: the need for small refrigerators, cost versus reliability, price versus volume, pulse tube progress, production line cost versus year, technology drivers, and notable quotations.

Before flying to this workshop, I pulled out my file on refrigerators. I've looked at refrigerators carefully only three times in my life, once was in 1970, once in 1982, and for the third time at this meeting. On the plane, I reread Jim Zimmerman's articles[1-10] from the late 70's, when he was developing his Stirling machines and was pointing out that many cryocoolers are oversized. In my earlier talk on SQUIDs and cryocoolers, I showed a drawing of one of the one-milliwatt NBS cryocoolers that used twenty watts of wall plug power. Ralph Longsworth showed us one of the APD machines that ran at helium temperature using on the order of a kilowatt. There's a continuum of

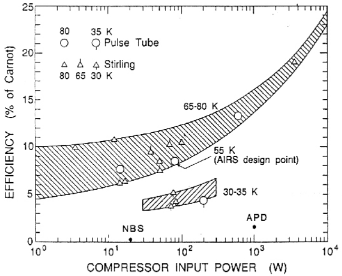

FIGURE 1. Compressor power versus efficiency. (From R. Radebaugh, these proceedings, with the NBS and APD helium-temperature machines added)

[1] This paper is based upon a transcription of the video-taped presentation. In editing it, I have chosen to maintain the informal, conversational style of the presentation, but I have had my hand-drawn illustrations prepared during the workshop redrawn. Whatever changes were made were for the sake of clarity or accuracy.

points, we would assume, in between. In Figure 1, I have added these two points to the graph from Ray Radebaugh that described the relationship between compressor size and efficiency of warm, large machines. I will now argue that there is space in the world for smaller machines.

Zimmerman stated that "to specify future cryocooler requirements solely in terms of refrigeration capacity at the cold end is misleading." He argued that you need to specify within reasonable limits the weight and volume of the instrument package and the number and size of wires, and then give the designer the responsibility and flexibility to design the total integrated package. I think we have worked hard in this conference to get those specifications as a package. He then argued, and again this was back in the late 70's, that the designer needed to integrate in its entirety the refrigeration system, the electrical leads, the radiation shields, and the support structure. And so with the exception of the single chip electronics package that would have "a standard interface," it's probably misleading to say, "Well, gee, let's build the ultimate 4 K cooler and then hang anything on it ranging from a fish parasite detector, to a Josephson Volt, to Doc Bedard's crossbar." One of the things that was pointed out is that you can imagine, for example when you start integrating a pulse-tube system, that you can take a multi-staged pulse tube and start doing imaginative things where you wrap the pulse tubes around the instrument to merge the instrument with the cooler. So there is a case where if you don't integrate the entire package, you could have a either a problem or a sub-optimal design.

I would argue that the MRI recondensers, such as the Boreas system, may be major overkill for digital electronics, unless you're running with thousands of wires or you have cryo-CMOS that is dumping all sorts of power into high temperatures. I say this because if you look at power requirements, Zimmerman estimated that the RF SQUID would dissipate a picowatt, the transition temperature bolometer a tenth of a nanowatt, and the SIS diode for radioastronomy 10^{-8} watts. I gather that the Josephson voltage standard dissipates on the order of twenty milliwatts RF power, and there are some wires. Doc has said that for the crossbar, this might be a watt. Right now, in terms of digital electronics, this is the maximum one might imagine. You have parasitics--Zimmerman estimated that an idealized theoretical wire pair might give you 300 μW; Doc says that it is 30 μW. The Tektronix report here said they could build a pair for 740 μW. The Josephson Volt requires only six wires; it has two that have to be copper, and four that can be high resistance, and the waveguide for the microwaves is dielectric so that's not even a source of power input. In fact, if you look at these kinds of numbers, the Josephson Volt is not adding very much power to the microwave power so, you're still doing the Josephson Volt for less than one hundred milliwatts. While Doc will encounter a watt of thermal leak down all the wires for a large crossbar, the other systems that we have considered at this workshop are much more modest in their parasitic loads.

In terms of radiation, there's a great deal that can be done with careful cryogenic design. I think it's recognized that Bill Goree's dewars are among the best. He's done a variety. The one I had numbers for is a seventy-five liter dewar that has a stainless steel neck tube, a 15 K cryocooler, five milliwatts going into the helium, and a six hundred day hold time (although, as Doc points out, this includes efficient use of the enthalpy of the cold helium boil-off). Zimmerman argued, in one of his old papers, that he could design a one kilogram instrument that had a package that was hung by spun glass fibers that could support 10 g accelerations. The thermal load into this, properly insulated, was 6 μW, which would require a Carnot room temperature power of 444 μW; if you put in a one-percent efficiency, you would essentially require only 40 mW of wall-plug power to cool the radiative load! So the powers for thermal radiation are small. The parasitics can be very large, and the devices themselves are very low power, so in many cases a lot of the power that we have been talking about today is overkill, at least for the digital electronics, unless you start putting in things like cryo-CMOS which could dump lots of power into the warmer stages. So I reiterate that it is important not to over design the thermal requirements.

Another key point relates to cost versus reliability. We were shown the data in Fig. 2, most of which were for moderately warm systems, with the space Stirling at the top, a hypothetical commercial goal beneath it, the 15 K cryopumps in the middle, and the 80 K tactical systems. I asked Ray what the automotive goal might be used for, and he said it is for a hypothetical collision avoidance system. I thought it might be for heat-seeking missiles. You can now ask "Is the reliability of a space system really required for the commercial goal?" My view is that the need for reliability has been vastly overstated, in that very few things on the ground have that kind of reliability. The mean time to repair for an automobile is several hundred hours or less. Simply utilize redundancy, repairability, and planned maintenance.

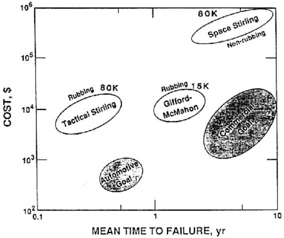

FIGURE 2. Cost versus reliability for cryocoolers, with temperature in kelvins. (From R. Radebaugh, these proceedings)

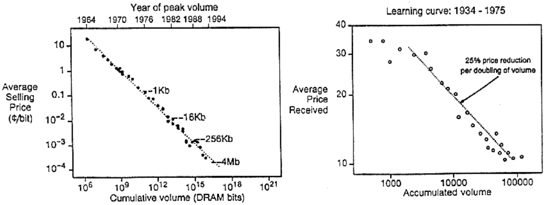

FIGURE 3. Cost versus cumulative sales for DRAM (left) and broiler chickens (right). (From R. Howard, AT&T Bell Laboratories)

Now let's look at the scaling issue. Figure 3 shows graphs that I got from Richard Howard at AT&T after he presented a rather challenging talk at the 4th International Superconductive Electronics Conference in 1993. On the left, it shows the cost per bit for silicon DRAM as a function of the total number of bits that had been produced. He showed that this curve has been falling at the rate of a 30% drop for every doubling of the cumulative volume. Rich went on to say that he believes this is a fundamental scaling law with some deep inner meaning, because the same behavior describes the production of broiler chickens, shown on the right side of Fig. 3. With broiler chickens, there was a 25% reduction per doubling the volume. So we're now talking about between 25 and 30% reduction per volume-doubling. I ask where are we today with regard to 5 K cryocoolers? I've polled a number of people at this meeting, and the best I can figure is that the 5 K cryocooler market has an installed base, not (I guess) including the ones that have died, that is on the order of hundreds. Some people say a hundred, some people say several hundred, but we don't miss by much if we relabel Fig. 3 for broiler chickens to get Fig. 4 for 5 K cryocoolers. Given this graph, I claim that we are just at the break point where the up-until-now level price starts dropping with volume. But the volume we're talking about is not annual sales, but the total installed base. So it's important to realize, if you take this model of Rich Howard's, that if you want to halve the price, you must increase the installed base 4 to 5 fold. Which means you can halve the price of cryocoolers, if instead of several hundred, we have a couple thousand in place. You can cut the price by a factor of 10 if you increase the installed base between 90 to 250 fold, depending upon whether we use the high technology DRAM 30% factor or the low technology broiler chicken 25% factor.

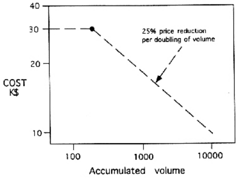

FIGURE 4. The price versus cumulative volume for small, 5 K cryocoolers. (Adapted from Fig. 3)

Given this perspective of the scaling problem, we can take those numbers, apply them to the cost-versus-reliability data for cryocoolers in Fig. 2, add some guesses of installed base, and we come up with Fig. 5. For space Stirling, there have probably been a hundred made at the most; maybe it's fifty. The estimate I get from asking people here is there might be fifty thousand to a hundred thousand GM cryopumps out there, and someone mentioned that there was on the order of a hundred thousand tactical systems. And, you say "Great, let us assume that we take this exact same technology and use the scaling rule for increase in volume to get from the space system to the high-reliability commercial system and do it solely by volume." It turns out that you need between 800,000 and 6,000,000 installed Stirling coolers to get the space system that cheap. So when people ask "How many space-qualified cryocoolers do you have to sell to get the price down by two orders of magnitude?" the answer is "A hell of a lot!" TRW would be thrilled to supply them. The truth is, however, that you're not going to put a space-qualified cryocooler on the street because you don't have the same constraints of power, weight and physical size. But by the same token, you must next ask yourself about the GM systems, which are now running on a hundred-dollar Grainger compressor. Well, if you need a 2,000 to 12,000 increase in installed volume to get the price down by a factor of fifty for an automobile system, you're talking about an installed base of about 200 million GM cryocoolers. For all of these numbers, we may have to add a factor of two because the data on this graph are for nitrogen temperature systems, while we must get to the HYPRES request for a low-cost helium-temperature system. So we double the price and double the required installed base to match. That's a billion space-qualified cryocoolers, or a half-billion cryopumps. What I argue from this graph, as absurd as the arithmetic sounds, is that you are not going to meet the stated price goals unless you change the technology.

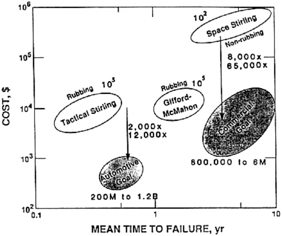

FIGURE 5. Cost versus reliability for cryocoolers, the installed base, and the required increases to achieve the goals. (From Figs. 2 and 4)

I find it a very sobering statement that you're not going to build 3 stage GM/JT systems and get the desired price based solely on increases in sales volume. In the short term, systems like the Boreas cycle may go a long way toward meeting the price/reliability goal, but in the long term, we still need a new technology. So the question is, how do you change the technology? The latest technology that we're seeing is the pulse tube, which I believe is one of the neatest advances in cryocoolers in the past couple of years. In Fig. 6, we see an existing, three-stage pulse tube that can get to 3 K. People are arguing that the installed base on pulse tubes isn't very large and the experience isn't very great, but that's fine because we're in the process of a change in the technology that may be comparable, to trying to look at the cost-versus volume curves for vacuum tube DRAM rather than silicon DRAM. I would hope so.

To show how pulse tube systems are improving with time, I took Ray Radebaugh's table of pulse tube performance and graphed it in Fig. 6. At the top left is the early Gifford data, and below and to the right are data for later systems. These are all valved or valveless systems. At the top right is the Wheatley resonant device, which is a latecomer. Below it is the TADOPTR, which we argued is based upon an entirely different principle. All in all, there has been a very nice decrease in cold stage temperature with time, including the addition of a second stage. A third stage has reached the 4 K mark. The three stage pulse tube system can get to 3 K, which means you have an adequate temperature reserve for regulation.

Suppose you said "What if I want to build a plant to produce pulse tube refrigerators? How much will it cost?" Well, the left-side of Fig. 8 is another one of Rich Howard's slides showing the capital investment for a semiconductor production line as a function of time. Somewhere around 1995, I don't know exactly when it comes on line, we see the billion dollar Intel plant in Scotland for the Pentium. Rich argued that the Intel plant is more or less on the older time-line. Well that's for the semiconductor industry. We need a comparable graph for the cryocooler industry. So I got two data points. I asked Peter Gifford, "What was the capitalization of Cryomech in 1982?" He said, "Maybe fifty thousand dollars, on a good day." The left-most point on the right-hand graph in Fig. 8 is essentially the cost of the Cryomech "factory." Yesterday, Boreas said that they could produce as a new product line the Hypres-specified cryocoolers for something on the order of six to seven hundred thousand dollars. So, we now have the two points on the curve for the correct dates, and this will allow you to extrapolate the cost of installing a production line to produce the coolers that you need to get the volumes up by the factor of a thousand to get the prices down. I'm not going to do that.

Next, we need to address the fact that in order to get the volumes up, we need technology drivers. If you look at the cryocoolers that we have been seeing for the past two days, there are a number of different technology drivers. The 60 to 80 K systems were clearly driven by IR tactical and IR space applications, neither of which had any financial concerns (at least by our standards). The cryocoolers for HTS telecommunication filters are going to benefit very much because of the earlier refrigerator development, but they will clearly have both temperature, space and performance requirements that are going to be rather pressing because of competition from other technologies. The 15 K GM refrigerator has obviously been driven by cryopumps, and it's important to realize that there may be a hundred thousand of them out there. For the 5 K market, the installed base is now on the order of a hundred, maybe several hundred, so there are no single giant technology drivers for 5 K coolers, but several small ones. We've seen MRI recondensers, but there are economic arguments as to whether they will fly in the western world. Radio astronomy is a small but steady market. Physics labs are a main force, but for a wide variety of specialized applications. Maglev could well prove to be a driving force--it's clearly one in Japan. And we're seeing NMR, MRI and specialized magnet coolers. I claim from what we've seen so far that LTS digital electronics is not a technology driver today, but it's perfectly capable of riding along on this market in the short term. Doc Bedard is benefitting from having the Boreas system, since he did not pay all the development costs and the Boreas system is a good fit to the crossbar. However, given the numbers here and the arguments from the preceding graphs on scaling and size, a hundred unit-per-year instrument, probably not the Josephson Volt but possibly a high performance oscilloscope, could change the situation to the extent that LTS digital electronics could soon become a technology driver for cryocooler development.

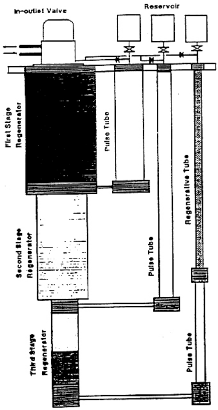

FIGURE 6. A three-stage pulse tube refrigerator. (From Y. Matsubara and J.L. Gao, Cryogenics 34: 259 (1994))

Finally, we can turn to paraphrased quotes. Elie opened with the statement that "Significant advances in cryocoolers in the past few years have led to a quantum leap in performance." From the discussion of Ed Edelsack's questions, I think we agree. I believe that "The Man from La Mancha died" is probably an overly pessimistic quote, but Arnie Silver is not here to defend himself. Someone said earlier that "a ten fold increase in sales would halve the cost." If you look using the numbers from Rich Howard's model, that's a 4 to 5 increase in the installed base, and the numbers we're talking about are sufficiently small, particularly at 4 K or 5 K, that if you increased anyone's production by a factor of ten you would quickly have a major increase in the installed base. It's important to realize, when you look at the competition between low temperature electronics and silicon, that "a billion dollars for that Intel line in Scotland" is rather sobering. "Photocopiers are unreliable yet invaluable" is one of the reasons that you don't have to worry about cryocooler reliability all that much. Then you run into the interesting regulation problems, such as "recondensers are virtually illegal in Japan". The statement "There is a 36-month window on commercial installation of LTS digital electronics," is sobering, and I'm not sure I completely agree with it although it has a definite ring of truth. I believe that the Josephson Volt and the very high speed analog-to-digital convertors can be commercialized within that window. Magnetometers and detectors built around digital SQUIDs should make it, too. I think that it's also valid to say that "Successful insertion will require integrated superconductors, semiconductors, and cryocoolers." It became clear that cryocooler requirements are "an n-dimensional non-orthogonal set," since much of the discussion we had was because various people were trying to optimize different dimensions for different applications. Now here is an important message

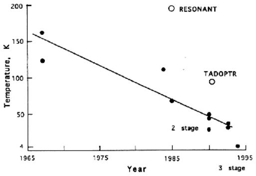

FIGURE 7. Pulse tube temperature versus year. (Drawn from data by R. Radebaugh, these proceedings)

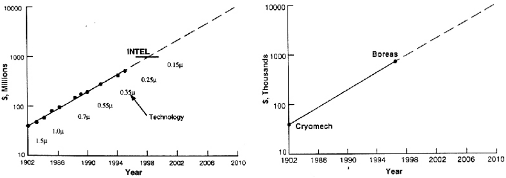

FIGURE 8. Capital cost for production lines for semiconductors (left) and cryocoolers (right). (Adapted from R. Howard, AT&T Bell Laboratories)

from this workshop: "Technology push takes 12 to 28 years and technology pull takes 4 to 6 years." So, as someone who's interested in the SQUID electronics business, I would like to urge that the cryocooler community feel a very strong technology pull, in that the cryocooler manufacturers should be pulled into building the cryocoolers that we need so we can quickly and successfully complete the push for commercial, low-temperature superconducting digital instrumentation.

I close with a final quote, which is mine: "If an economical, compact, reliable 5 K cryocooler can be built at modest cost, not low cost, but modest cost, much of the apparent attractiveness of high temperature superconductivity and silicon systems will be offset by the increased capability of LTS digital circuits." The two candidate products that are on the immediate horizon are the Josephson Junction Voltage Standard and the Fast ADC. Based on my earlier talk, I would argue that a 64-channel digital SQUID fish parasite detector for an Alaskan fish processing line is also a candidate, although not quite as far along as the Josephson Volt and the Fast ADC. (In this application, the appeal for digital SQUIDs arises from the need for not a single SQUID but a large SQUID array, and cryocoolers would be required because fishermen have trouble transferring liquid helium on factory ships.) As I said earlier, there are short-term solutions to the Hypres cryocooler specification, such as the clever Boreas cycle in a smaller configuration than the MRI recondensors. In the long-term, I believe that the technology that seems promising today might be either a three-stage pulse tube or a hybrid pulse-tube/JT. Possibly other approaches will begin to compete, such as advanced thermoelectric or optical cooling.

So that is my outsider's view of the present state of 5 K cryocoolers. I hope that my comments have conveyed my enthusiasm for combining cryocoolers and LTS digital electronics.

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