While cryotronics is, to some degree, a rather special technology, it has not been possible to show that cryogenic circuits possess, on balance, any functional advantages over circuits realizable in competitive technologies. Accordingly, the only real promise for cryogenics would seem to lie in the possible cost advantages which might, in principle, be realized through the batch manufacturing of large integrated circuit modules. That such an advantage can be realized in fact is, at present, somewhat problematic.

The principal costs in the cryogenic technology are found to lie largely in five areas, namely: design, mask layout and checking; mask fabrication; circuit deposition; packaging; and refrigeration. A review of the steps required to carry out the construction and assembly of complete cryogenic processor indicates that, in terms of present technology, considerable cost reductions must be realized in each of the above areas if cryogenics is to be made commercially attractive.

The current state of the cryogenic technology is reviewed and an attempt is made to project the cost structure which would appear to be realizable in the near future.

It is appropriate, in presenting the case for cryogenics, to begin with two judgments which are, a priori, the basis for the central arguments which follow.

A. The technical problems which need be solved in reducing the cryotronic technology to practice are, within reason, developmental rather than fundamental in nature, i.e., no fundamental "breakthroughs" or major innovations are believed to be required.

B. The cryotronic technology, while possessing a number of special features, is functionally equivalent, on balance, to a number of existing technologies and must, therefore, be evaluated basically in terms of the function it can provide for a given cost.

If we admit these judgments as fact, it is now expedient to examine a number of the costs which underlie the production of cryogenic hardware and to then examine a number of applications for which cryotronics has been considered.

One of the major costs in the fabrication of cryogenic integrated circuits is that associated with the design and layout of the composite circuit and the generation of the artwork from which the stencils or masks for deposition are eventually fabricated. For complex logical circuits where redundancy or modularity is low, it has been estimated that about one man hour of labor per cryotron is required to manually produce the detailed designs for a complete set of deposition masks.

It is apparent that the mask designs for a circuit containing, say, 5000 cryotrons could easily cost tens of thousands of dollars and that it would be necessary to produce thousands of circuits in order to economically absorb such design cost. Obviously much can be done to automate the design process and computers are already being used to assist in the layout and checking of circuit patterns. It would appear, however, that even with automation, design costs may be high enough to limit the use of large integrated circuits to applications where the circuits are highly redundant or extremely modular, e.g., memory.

THE CASE FOR CRYOTRONICS?

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From the collection of the Computer History Museum (www.computerhistory.org)
The fabrication of precision masks is, at present, a rather costly process which adds significantly to the cost of the finished circuit. Typically, several dozen masks are required for a complete circuit and the precision masks have a rather finite life due to the necessity of periodically cleaning them of evaporated material. It appears that much can be done to lower costs in this area, but it is equally obvious that substantial work must be done to provide large precision masks economically.

Vacuum evaporation is currently employed as the central technique for depositing cryotronic circuits and experience has shown that an automated and sophisticated production facility is not particularly inexpensive either to construct or to operate. Economic production of circuits is possible only if the "throughput" of the system is high and it is possible to produce circuits in volume. Economic production does appear possible, but a cursory examination of most of the present production systems is sufficient to indicate that considerable work must be done to provide for decreased cycle time in the fabrication process and for true on line "batch fabrication."

Packaging of cryogenic circuits is both a technological and economic problem. Obviously, low impedance interconnections are required and it is desirable to hold the number of interplanar connections to an absolute minimum. Demountable connections appear to be necessary for economic assembly and disassembly of arrays. Within limits (and depending on the application) the problem is not insurmountable, but the difficulty of making numerous or lengthy connections between substrates does appear to limit seriously the general applicability of the cryogenic technology. Here again, cost must be borne in mind and, unfortunately, the cost of the "precision" connectors required for high-speed coupling is nonnegligible.

Finally, the cost of refrigeration must be weighed in evaluating the performance of a cryogenic processor. Costs of closed cycle refrigerators are, at the present time, prohibitively high, and virtually rule out the serious considerations of cryotronics for any application. On the other hand, such units are in their commercial infancy and it is obvious that initial production costs will be significantly reduced in time. The cost of servicing and maintaining such refrigerators is still unknown, but hopefully this will not prove to be a serious problem.

With the above factors in mind, it is convenient to now consider the potential of a number of proposed cryogenic applications.

1. Continuous Film Memory. This type of memory, wherein storage is provided by circulating supercurrents which are trapped in a superconducting sheet or film, is functionally equivalent to conventional magnetic core or thin-film memories. For very large memories, superconducting storage appears to offer a number of advantages over conventional room temperature storage. Basically, the technical advantages accrue from the fact that the back emfs and signal attenuations on the drive lines are small when the lines are superconductive and from the fact that the signal to noise ratio on the output is virtually independent of the size of the memory array (due to the screening of the superconducting sheet). These advantages result in reduced costs in the memory driving and sensing equipment, particularly as the array size is increased. Further, since the storage array can be batch fabricated together with the memory decode network, it would appear that very large memories could be fabricated quite economically.

In many ways this application appears to be ideally suited to the cryogenic technology. Plane design and layout is simple and all planes in the memory are redundant. The number of edge connections per plane is small in comparison to the number of elements contained on a plane and interconnection is not a serious problem. The duty cycle in such an application is relatively low and power dissipation is the decoder and memory array is trivial (of the order of a milliwatt at a megacycle operating rate). The chief power dissipation comes from the lines leading into and out of the helium bath and very modest refrigeration is required for a sizable memory.

2. Associative Memory. This type of application combines some of the simplicity inherent in memory with some of the advantages gained by utilizing the logical capabilities of cryotrons. Like the continuous film memory, planes can be used redundantly; the duty cycle (and hence the power dissipation) is low; and the number of interplane connections is modest. The application is quite obviously an appropriate one for the cryogenic technology, but it is not certain at this time
just how significant an application can be made of associative memories themselves. This question is obviously quite debatable, but it appears probable that cryogenics could be a significant technology for special purpose processors of this general class.

3. General Logical Processors. It is in this area that the future of cryotronics is least assured. The projected performance of in-line cryotron circuits is roughly comparable to the performance expected from high-speed transistor circuits. In principle, cryotrons would appear to offer possible cost advantages through the batch fabrication of the integrated circuit planes. Whether this basic advantage will be lost in the costs of design, packaging, and refrigeration is, at present, unknown.