INTRODUCTION

Superconductive phenomena and their potential application have received much attention for several years. The low temperatures required have most often been provided by cryogens, with the presumption that when the time comes, suitable refrigeration equipment will be available.

DISCUSSION

When one says “suitable” it generally means “reliable and inexpensive.” Simple words; but what do they mean? The technician who, with considerable effort, gets his liquefier working again knows what unreliability is. The communications engineer who experiences 0.01% unscheduled downtime from his unattended cooled amplifier system also knows what unreliability is—but they are not speaking the same language. The words are the same, but the standards are different. The same difference will emerge when superconducting electric power transmission cables emerge from the national laboratories and into the public utility. “Inexpensive” also has different meanings. To the national laboratory, it means low cost. To the communications engineer, or to the public utility engineer, it means high cost-effectiveness.

The 4 and 20 K refrigerators built by one refrigerator manufacturer and used for cooling ruby maser and parametric amplifiers on the earth stations of satellite and space communications systems now have over three million hours of accumulated operating time. According to Comsat Technical Review, these machines have demonstrated in excess of 20 thousand hours mean time between failure (MTBF). Outages due to cryogenic system failure accounted for only a small fraction of 1 hr per year. This is the kind of reliability that is required by a public utility. Unfortunately, the communications network is the only example of such high availability of cryogenic systems, but it does demonstrate that it can be achieved.

There is a tendency to focus on the reliability of key components, as if this were the measure of system reliability. For example, a refrigerator using gas-bearing turbines is considered inherently more reliable than one using oil-bearing turboexpanders, and much more reliable than one using reciprocating expanders. Such thinking reveals an ignorance of the basic issues. When you expect a refrigerator to work, you are concerned with its availability; i.e., is it working when you want it to? This involves at least three aspects. First, is it capable of doing the job under the
extremes of environment that it may see; second, is it reliable enough to accomplish
its mission, which may be to operate for, say, 3000 hr between routine maintenance
periods; and, third, is it maintainable?

Let us now consider a specific case. A helium liquefier designed to produce
750 liters/hr was put on stream and produced less than 500 liters/hr. It was initially
asserted that the heat exchangers or the expanders were defective or that the basic
design was inadequate. A turboexpander failure did occur. An air leak into a liquid
helium transfer line caused an air–ice bridge to build up between the vacuum­
insulated helium line and the outside wall. This caused a reduction in the liquefaction
rate—which caused a change in the gas flow pattern in the liquefier; this, in turn,
caus ds an adsorber bed to be by-passed, allowing contaminants to enter the
turboexpander. This caused freezeout of contaminants in the expander and finally
resulted in turbine failure. Where was the design at fault? Perhaps the answer is that
the system design did not anticipate an air leak into a transfer line.

After this and a few other minor failures were corrected, the unit ran very well.
This liquefier has since operated for over 14 thousand hours. During that time it has
had one oil pump motor failure, one diffusion pump heater failure, one broken
control line, and one liquid nitrogen supply failure. These four failures in 14
thousand hours of operation, equivalent to an MTBF of 3500 hr, were all trivial
failures (trivial in the sense that they were easily corrected and did not cause
consequential damage—but failures nonetheless.) It is worth noting that none of the
failures were connected with a key component, such as a compressor, heat
exchanger, or expander.

This plant is considered to be highly reliable. Its mission is to produce liquid
helium to customers as required. It does this. Operating 65% of the total available
(8750 hr/yr) time, it has produced over ten million liters of liquid helium. However,
would this performance be considered adequate for cooling a superconducting
electric power transmission line?

The plant is given routine maintenance every 3000 hr. On an organized basis
this would take about 15 hr. This would give superficial availability of 3000/3015 =
0.995, or 99 + %. However, the unscheduled downtime because of random failure,
the time to detect, correct, and reestablish operation, might be 48 hr. The reliability,
that is, the probability of not having a failure between routine overhaul, is given by
\[ R = \exp(-\lambda t), \]
where \( \lambda \) is \( 1/\text{MTBF} \) and \( t \) is the time between routine overhaul or the
mission time. In this case \( R = \exp(-3000/3500) = 0.424 \), or a 57.6% probability of
failure. This presumes that 3500 hr is the true MTBF. However, with only four
failures to judge by, we could say, with a 95% confidence factor, that the true MTBF
is between 1850 and 14,700 hr. Only more running time will tell us what the real
reliability is.

If we take the lower number, with which one has a 95% confidence factor, then
\[ R = \exp(-3000/1850) = 0.198, \]
or an 80.2% probability of failure before the next
overhaul. If we consider ten such systems in series for a 100-mile superconducting
transmission line, then we have \[ R = \exp(-3000/1850)^{10} = 0 \] or an almost absolute
certainty of a failure between routine maintenance. Such reliability is not good
enough for a public utility. For a 750-liter/hr liquefier, it is acceptable; as a 2–4-kW,
4 K refrigerator for utility use, it is not.

If a standby refrigerator were provided at each station, and enough liquid
helium storage were provided to cover the cooldown time of the standby unit—say
5 hr—then we would be concerned with the probability of failure of the standby unit
while the failed unit was being corrected to be placed in standby condition. Now the